A Qualitative Analysis of Acid Mine Drainage in Watershed 29, of the Moxahala Creek and its Tributaries, Perry County, Ohio.

A thesis presented in partial fulfillment of the requirements for the Degree of Bachelor of Science in Geology and Mineralogy and in cooperation with the Division of Reclamation--ODNR.

by
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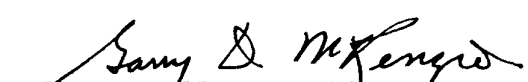
June, 1980

approved by



Dr. Garry McKenzie, Advisor

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Abstract

The lower Moxahala Creek watershed in Perry County has undergone surface and subsurface coal mining operations. The major coal seam mined in this area is the Middle Kittanning or no.6 coal.

The high sulfur content (6.5%) of the coal, and the presence of pyrite and marcasite in the surrounding strata contribute to poor water quality discharging from mined areas.

Three major contributors to acidic flow in this region are runoff from spoil banks containing large amounts of pyritic material, runoff from coal refuse piles left in final cut valleys, and seepage from final cut lakes through spoil banks, and into adjoining waterways.

Controls suppress the oxidation process contributing to the acidity of the Moxahala basin. Thermodynamic controls favor the total elimination of oxygen from the reaction site, returning it to a reducing environment.

Kinetic controls repress the catalyst causing rapid oxidation of ferrous iron by introducing bactericide agents into the mine before the water escapes.

Acknowledgements

The writer wishes to extend her appreciation to Dr. Garry McKenzie, who acted as the advisor for this project. He provided an abundant amount of reference materials, and his suggestions and criticisms proved to be most enlightening. Most important, was his patience and good humor, which made the writing of this report much easier.

Thanks are also given to Dave Buchanan at the Ohio Division of Reclamation, who originally suggested the study area in Perry County. He provided a number of references, maps and the materials used in the field. He also took time to explain specific field procedures before the project began. Dave is also responsible for arranging to have all of the samples tested at Stilson Laboratory in Columbus, Ohio.

Introduction

There are approximately 40 billion tons of bituminous coal reserves in Ohio, 17 billion of which are from underground mines. Today the majority of coal is mined at the surface. There are 27 active mining counties in southern and eastern Ohio, composing that portion of the state located in the low basin structure, or Appalachian Basin.

There are 350,000 acres in Ohio that have been affected by coal mining. The land is in various stages of reclamation, from minimal to total restoration (Buchanan, 1980, oral communication).

The two types of mining practiced in watershed 29 are underground mining and contour surface mining.

Contour surface mining is the major operation in use today. The coal is mined by following the outcrop of the coal seam along the contours of the land. In Perry County this method is quite effective. The strata dips approximately 2-3° east-southeast and may be considered relatively horizontal.

Underground mining cannot be detected from the surface topography. Evidence of subsurface mining is the presence of acid-mine seepage.

Figure 1 is a cross sectional view of a contour surface mine. The overburden above the coal seam is composed of a friable sandstone that easily decomposes. The sandstone high wall often times must be reinforced to prevent its collapse. The pond at the base of the high wall is a collection site for contaminated water. The toxic contaminants include iron hydroxides and acid. The nearby soil surrounding the mine is too

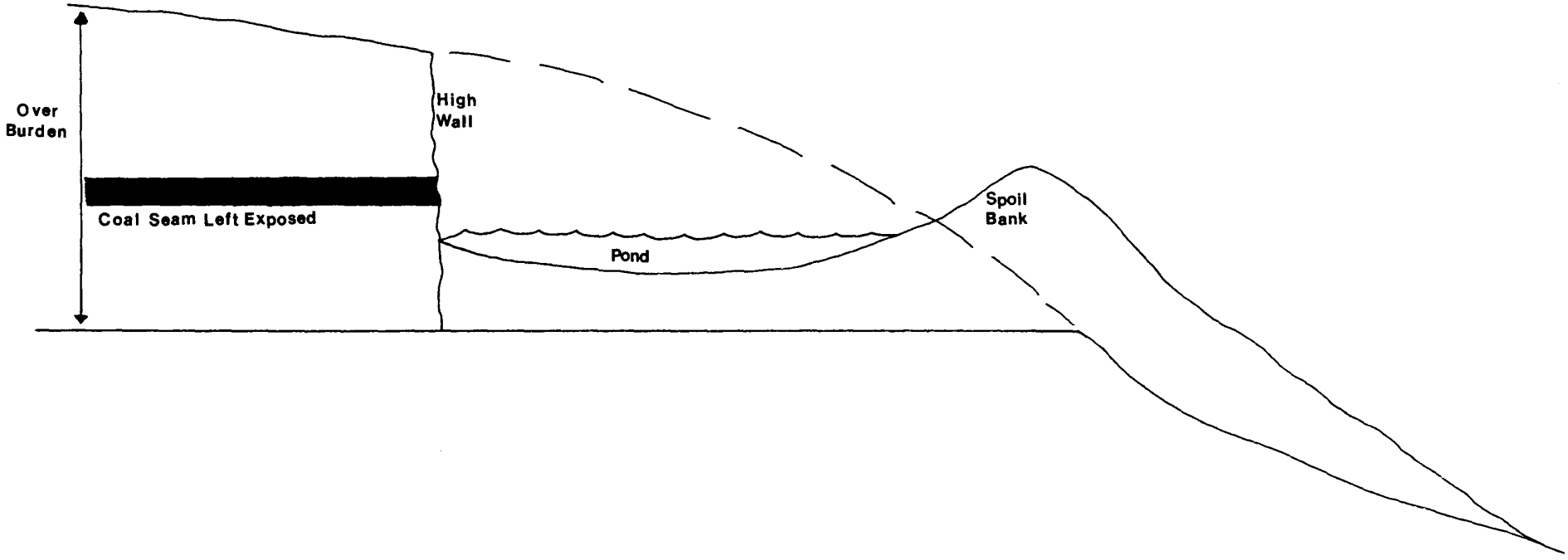

FIG.1 A cross-sectional view of an unreclaimed strip mine.

acidic and the erosion rate too great to allow vegetation to grow. Therefore, the re-establishment of vegetation in a surface mined area is extremely difficult.

The toxic material found in the ponds and soil is also present in the surface drainage from the mined areas. Surrounding streams have acidic waters, and high sediment loads due to the accelerated rate of erosion. The accumulation of the sediment is so great in some areas that it literally chokes the stream channels. The high erosion rate is a direct result of the disintegration of the overlying friable sandstone in the high wall. The build-up of sediment in the stream channel may be extensive enough to spill over into the adjacent flood plain thereby destroying the usefulness of the land for farming.

Study Area

The study area, located in the Moxahala Creek drainage basin is approximately 6.4 miles southwest of Zanesville, Ohio, 25.8 miles east of Lancaster, Ohio and 2.2 miles west of Tridelphia, Ohio. The major portion of the basin lies in Perry County, however, its boundaries extend into Muskingum and Morgan Counties. This basin is contained within four quadrangles: Fultonham, Crooksville, Deavertown, and New Lexington (see Figure 2).

In 1974 Skelly and Loy studied the major drainage basins in Ohio affected by coal mining operations. Seventy-nine watersheds were identified and examined. The Moxahala Creek was designated as watershed 29, and will be referred to as such throughout this

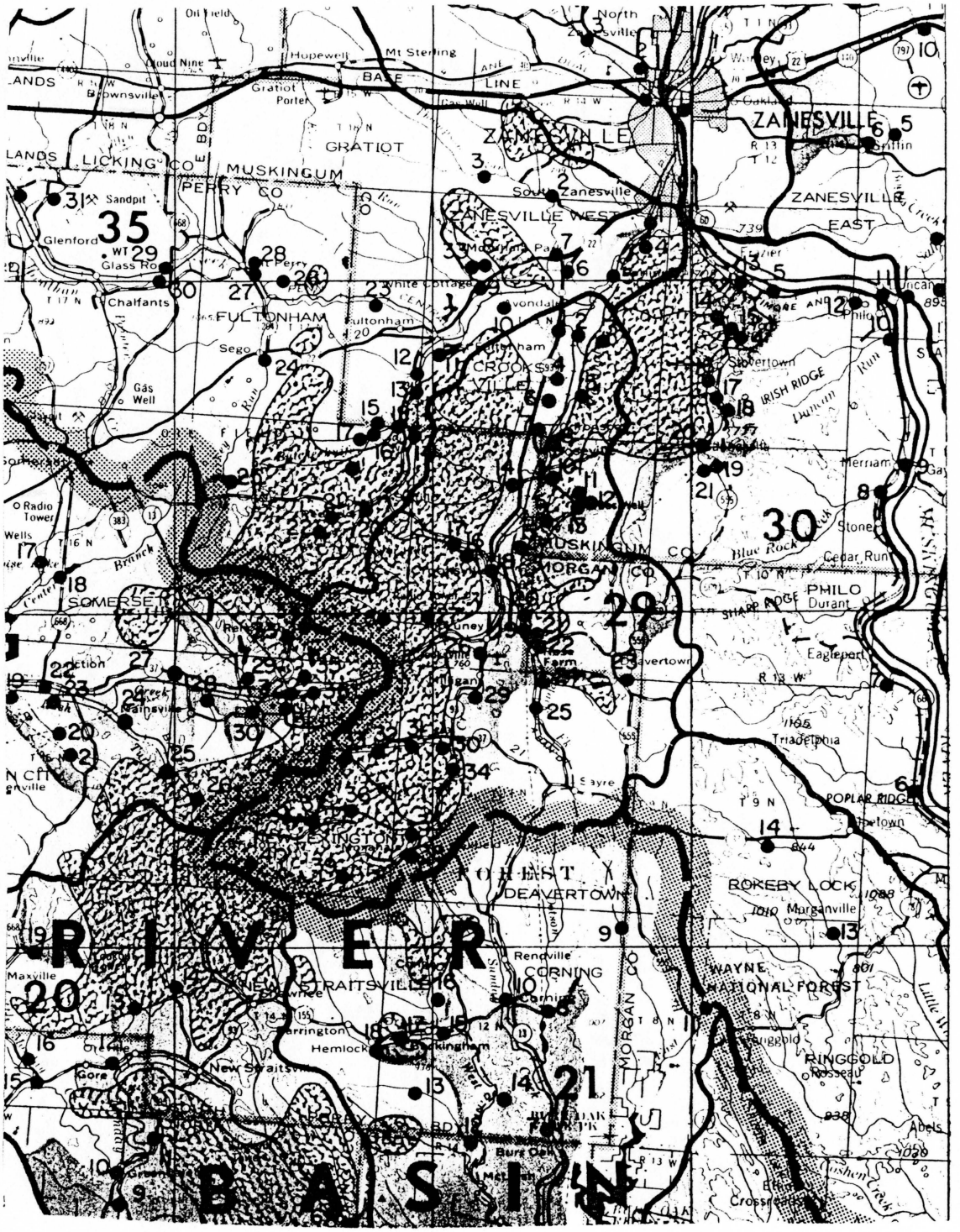

FIG.2 A topographic map of watershed 29, in Perry County (Stanley Engineering).

report.

The total area of the watershed is approximately 64534.5 acres. The Division of Reclamation--ODNR recently produced computerized printouts of maps graphically indicating the amount of reclamation needed in the watershed. The categories range from areas needing major reclamation to totally unaffected areas. Table 1 indicates the types of reclamation needed in the watershed in terms of acreage and percent area. These figures can be further broken down in terms of the four individual quadrangles. It should be noted that the number of acres in the watershed (64299.6 acres), on the computer printouts of the quadrangles, varies slightly from the computerized printout for the total watershed (64534.5 acres). Table 2 summarizes the types and percentages of reclamation needed in the four quadrangles under consideration.

The four quadrangles may also be viewed in terms of the number of square miles of land in need of reclamation

Quadrangle	Acreage	Square Miles
Crooksville	6224.1	10.14
Fultonham	3057.2	4.98
New Lexington	4742.8	7.72
Deavertown	1567.6	2.55

Methods and Field Procedures

Watershed 29 is located in the southwestern portion of the Moxahala drainage basin. The main tributary in the watershed is the Moxahala Creek, which flows northeastward into the Muskingum River.

Forty-two samples were collected either directly from the Moxahala Creek, its tributaries, or from collection ponds in the

Type of Reclamation	Acreage	Percentage
major	14680.4	22.75
moderate	425.8	0.66
slight	294.7	0.46
mine refuse pile	268.7	0.42
unaffected	48864.9	75.72

Table 1 The types of reclamation needed in watershed 29.

major - high acidity, no vegetation, massive erosion

moderate - acidic, some vegetation, erosion present

slight - slightly acidic, vegetation is successful, erosion is slight

Quadrangle	Type of Reclamation	Acreage	Total Unaffected Acreage	Total Affected Acreage	Percent Mined
Crooksville	major	5962.6	17113.8	6224.1	26.67
	moderate	29.4			
	slight	47.1			
	refuse piles	185.0			
	unaffected	17113.8			
Fultonham	major	3057.2	1033.5	3057.2	74.74
	unaffected	1033.5			
New Lexington	major	4259.6	10399.3	4742.8	31.32
	moderate	396.4			
	slight	85.7			
	refuse piles	1.1			
	unaffected	10399.3			
Deavertown	major	1323.0	20161.3	1567.6	7.21
	slight	162.0			
	refuse piles	82.6			
	unaffected	20161.3			

Table 2 The types of reclamation needed in the four quadrangles of watershed 29.

surface mines. The location for the sampling was selected on the basis of its representativeness of the area and the accessibility for collection (see Figure 3).

Two 1-quart polyethylene bottles were filled wih surface water from the sample site. One bottle was completely filled, and labeled NP (non-preserved). The second bottle was only partially filled. Nitric acid (HNO3) was added to the sample, the bottle was thoroughly shaken, and all air removed. This bottle was labeled HNO3. The nitric acid preserved the sample for later analysis in the laboratory, for the major constituents held in solution.

Each bottle was labelled with the following code:

MLR: mined land reclamation
PYC-291: Perry County, watershed 29, sample 1
NP: non-preserved
HNO3: nitric acid
location description
date of sampling

The water temperature and field pH were recorded for the non-preserved sample at each location.

Geology

The study area lies in the Kanawha section of the Appalachian Plateau. The eastern edge of the Illinoian Glacier extended just outside the western boundary of the study area. There is little topsoil on the hills, and topsoil in the valleys was transported there by surface flow from the melting glacier.

1 dips east-southeast, approximately 25-30 feet per mile. In the northwest portion of Perry County, the Waverly and Maxville Formations of the

Watershed 29

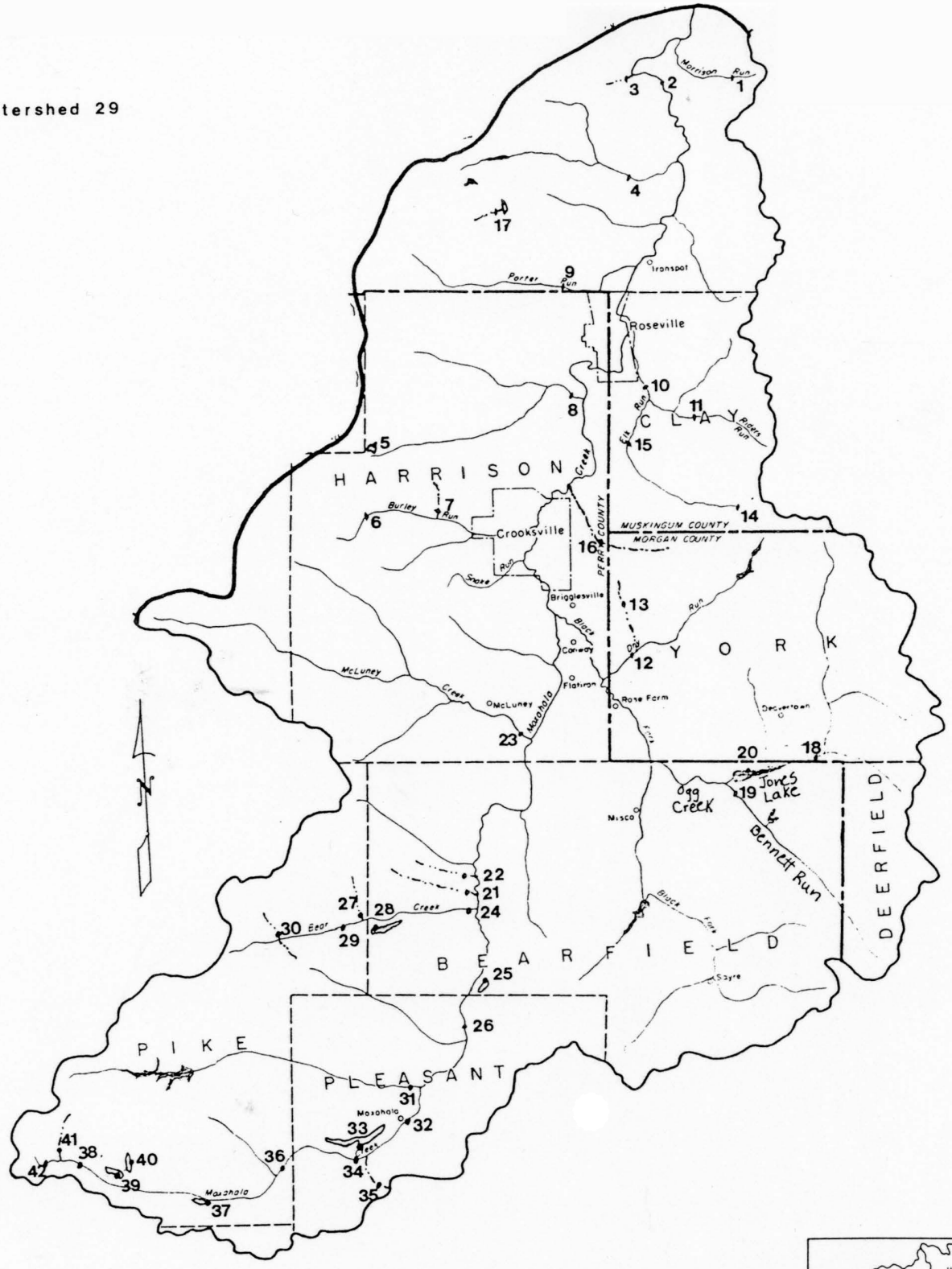

FIG.3 Locations of sample sites in watershed 29.

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SCALE IN MILES

Mississippian System are exposed. Towards the southeastern corner of the county, the Conemaugh series of the Pennsylvanian System is exposed (see Figure 4). The underlying strata in the study area are the Pottsville, Allegheny, and Conemaugh Formations of the Pennsylvanian System (Studlick, 1977).

The strata of the Pennsylvanian System are composed primarily of alternating layers of sandstone, shale, clay, coal and limestone. The strata are cyclic deposits of a fluvial-deltaic environment which migrated back and forth across the study area during Pennsylvanian times (see Figure 5). The shale layers, above the coal seams, contain pyrite and marcasite that are high contributors to acid production. The Middle Kittanning coal is divided into benches by narrow partings of clay and shale, both of which are sources for acid-bearing material.

The most valuable and most frequently mined coal seam in this area is no.6 or Middle Kittanning coal which is part of the Allegheny Formation of the Pennsylvanian System (Studlick, 1977). The thickness of the seam ranges from 2.5 to 14 feet, with an average thickness of 5.5 feet. Of lesser value are the no.5 coal or Lower Kittanning coal, and no.7 coal or Upper Freeport coal. These coal seams are also in the Allegheny Formation (Studlick, 1977 and Stanley Engineering, 1966).

Physical System

Introduction

Two types of pyrite-bearing systems exist, that contribute to acid production under natural weathering conditions. First

FIG.4 GEOLOGIC MAP AND CROSS SECTION OF OHIO

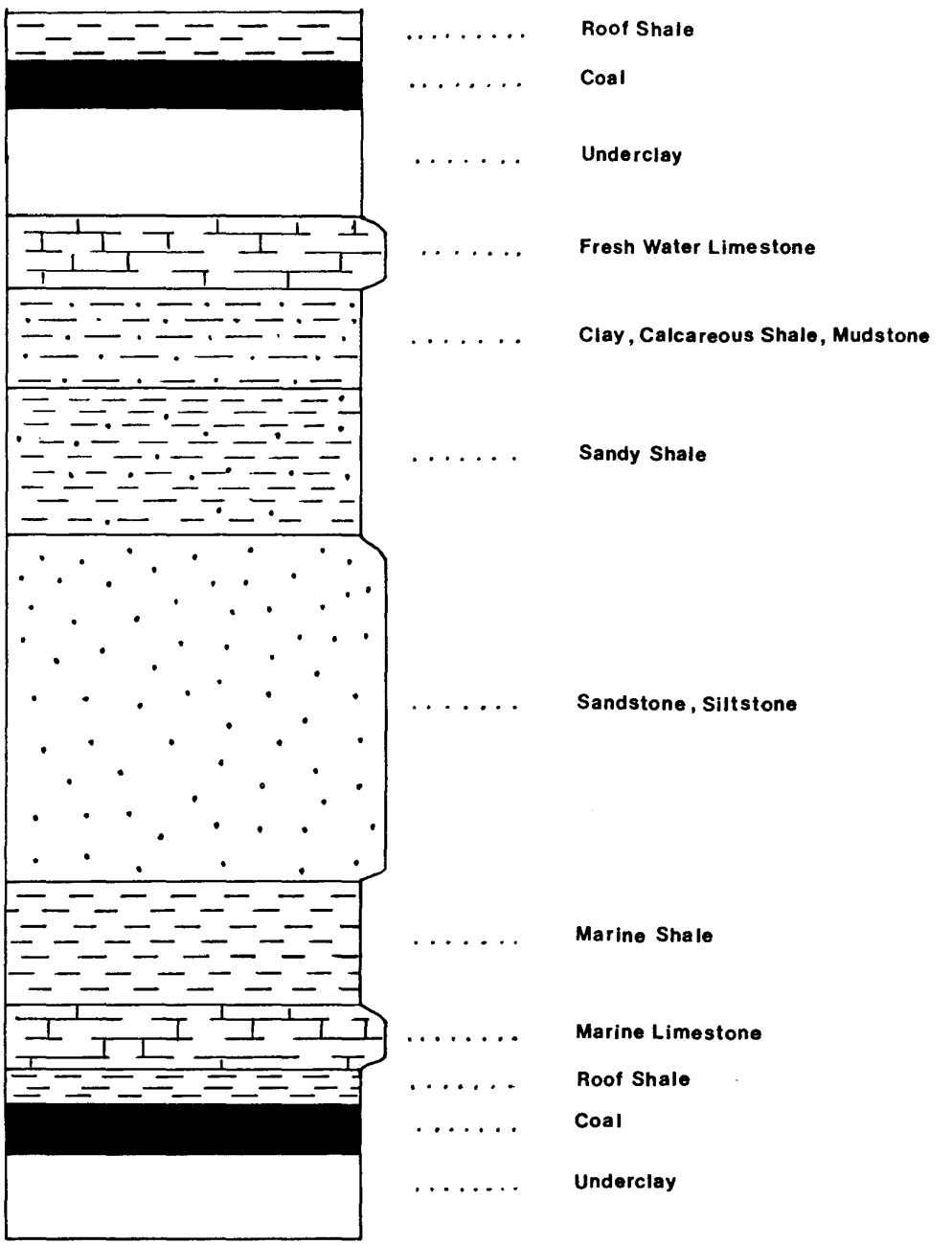


FIG.5 Stratigraphic column of watershed 29.

are under ground mines, where pyrite is left in place but exposed to an oxidizing environment. The second type is relocated materials, which include spoil banks and refuse piles. These are both characteristic of surface mines.

The physical characterization of a general pyritic system must include the following basic information.

1) type and location of the pyritic material
2) the location of the zone where the pyrite is submerged below the free water surface; under these conditions the pyrite is sealed off from the oxygen in the atmosphere
3) nature, location, and flow patterns of ground-water systems which are the mode of transportation for removing oxidation products from the pyritic system
4) physical characteristics of structures surrounding the exposed pyrite, which in turn helps determine the availability of oxygen into the system
(OSU Research Foundation, 1971).

The mode of transportation for the oxygen into the pyritic system is either by convective air currents, or by molecular diffusion through water or air (OSU Research Foundation, 1971).

Exposed pyrite in such a system has a continuous supply of oxygen to its surface. Pyrite covered by several inches of water is not considered exposed.

Underground Mines

Underground mines in Ohio are of the room and pillar type. Evidence suggests that large amounts of acid drainage come from up-dip drift mines in regions of bituminous coal (OSU Research Foundation, 1971).

The amount of mine drainage originating in the mines may be due to two different methods used in removing the coal. If the drift mine cuts into the coal seam above the permanent

ground-water table, then any water seeping into the mine will pass through pyritic material. Consequently, acid is produced, and seepage from the mine eventually drains into the surface water flow. In contrast, if the drift mine cuts into the coal seam below the permanent ground-water table, then water seeping into the mine must be pumped out during mining operations (OSU Research Foundation, 1971).

In examining the acid production from any underground mine, the following factors must be considered:

1) the amount of pyrite present
2) the location and flow rate of ground-water drainage systems
3) the rate at which pyritic surfaces are refreshed
4) the nature and location of points where convective air currents may enter the mine

(OSU Research Foundation, 1971).

To understand the factors above, and their contribution to the amount of acid produced, consideration must be given to the amount and movement of water within the system.

A rapid release of water will flush out, and drain the reactive surface in the mine. This rapid flow of water is a result of a sudden change in flow patterns due to an occassional heavy rain or seasonal periods of high drainage flow. A cycle of high and low discharges soon begins to develop. At low or no flow, the oxidation products accumulate on or near the reactive site (pyrite surface). When high flow dominates the environment, the mine is flushed out with water. The water in turn dissolves the salts that have collected at the oxidation site. This initial drainage solution from the mine is highly concentrated in toxic materials. Streams receiving these periodically intense surges of acid solution from the mine, will undergo "quality shock" (OSU

Research Foundation, 1971).

Two types of transport occur during the course of the two phases of the hydrologic cycle within the mine. They are gas transport, resulting in oxidation, and product transport or removal of the products of oxidation from the pyrite surface.

Gas transport is at its maximum when the flow rate is low, and thus product transport is at a minimum. Under high flow conditions, oxidation decreases, and product transport increases (OSU Research Foundation, 1971).

A description of fluid transport depends on the degree of permeability and porosity of the rock, and the jointing and bedding planes within the strata. Significantly high porosity and permeability characterize sandstone-type rocks. If the interstices between the grains are filled with a cement, such as clay, silica, calcite, or gypsum a decrease of porosity will be observed.

The mine can also function as an aquifer drainer. Mining operations result in the creation of large amounts of open space. Consequently, the mine can stimulate or accelerate drainage from the overlying formations. If the overlying strata are highly permeable, high drainage rates result. If the overlying strata are relatively impermeable a delay of drainage results until the mine collapses, whereupon, the water-bearing zones are exposed (OSU Research Foundation, 1971).

Bedding-plane joints are related to the sedimentation history of the rock. These joints become planes of weakness, parallel to the bedding that can develop into distinct planes

between layers of rocks. The jointing and bedding planes provide void spaces in the rocks and, therefore, become passageways for the movement of both water and air through the rock. Coal is often characterized by close sets of joints called cleats. Through weathering, gravity, and mass-wasting the joints can be widened near the outcrop and act as water passageways (OSU Research Foundation, 1971).

Surface Mines

When surface areas are mined, the coal seam is completely removed, and the overburden is piled nearby (see Figure 6). Acid-forming materials left on the surface and in spoil banks are readily oxidized. With each rainfall, acidic salts are washed into the natural drainage channels. Water flowing in the mined area also results in the erosion of the loose spoil, leaving greater amounts of acid-forming materials exposed to the atmosphere.

In surface mining operations, pyrite is left in place in the high wall where oxygen transport is restricted to the surface of the pyrite left exposed to the atmosphere.

The majority of acid production is from weathering of pyrite in spoil banks, where a greater surface area of pyrite is exposed to oxidation (OSU Research Foundation, 1971).

It is usually pyrite at or near the surface of the spoil bank that undergoes oxidation. It is unlikely that pyrite buried several feet below the surface will be affected because diffusion of oxygen cannot reach that deeply. The most reactive sites, therefore, are in the outer layers of the spoil bank. They are

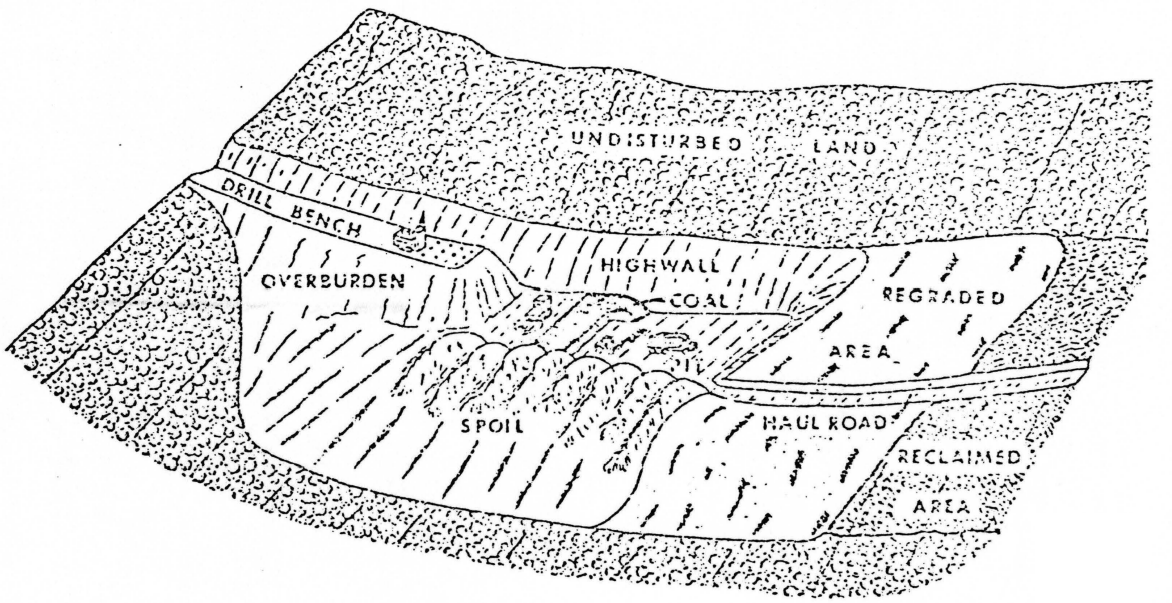


FIG.6 Typical contour strip-mining (From Skelly and Loy, 1975).

easily flushed out and refreshed by occassional precipitation, resulting in a fresh new surface being exposed to atmospheric oxygen.

Refuse piles are similar to spoil banks in their morphology. The pyrite content in a refuse pile is usually higher and the matrix is generally composed of clay minerals, such as kaolinite or illite. The pyritic material is more evenly distributed throughout a refuse pile, instead of being localized in one area, as in spoil piles.

In both spoil and refuse piles, the zone of weathering is dependent upon the "tightness" of the pile. A pile with high porosity results in greater air and water transport, and therfore the zone of weathering is thicker.

Chemical System

Introduction

There is a direct relationship between the chemical composition of natural water and the solid minerals in the strata with which the water comes in contact. The constituents of natural water are derived mainly from the soil and the solution of minerals in rocks. These dissolved or suspended constituents are comprised of silica, cations, and anions (Hem, 1970). The majority of anions are derived from nonlithologic sources. An example is bicarbonate, which is the result of CO2 absorbed from the atmosphere and trapped within the soil by biochemical means (Hem, 1970). Regardless of the sources of the cation or anion in natrual water, a balanced equilibrium is maintained between them in nature.

Lithology

The vast majority of rocks are heterogeneous, and therefore are a complex of various minerals. These minerals vary widely in their stability and solubility in water. Many minerals are hydrogen ion acceptors, and become common participants in the weathering of rocks. Most minerals, with the exception of evaporites, are not readily soluble in water. Sometimes a minor mineral constituent in a rock that is quite soluble in water will become the dominant control on the composition of the circulating natural water (Hem, 1970).

The strata underlying watershed 29 may be classified into two major categories; resistates and hydrolyzates (see Figure 7).

Resistates are rocks composed principally of residual minerals that have not been chemically altered by weathering of the parent rock. Examples are sands, gravel, sandstone, and other species composed almost entirely of unaltered fragments of other rocks (Hem, 1970).

Hydrolyzates are rocks composed primarily of relatively insoluble minerals that were produced during the weathering of the parent rock. These are fine-grained rocks composed primarily of clay minerals, and they include bauxites, clay, and shale (Hem, 1970).

Resistate sediments are composed of fragments that were resistant to the weathering process which broke down the parent rock. Only when these sediments come in contact with water do they become subject to attack and eventually break down. This

Element	Igneous rocks	Sedimentary rocks		
		Resistates (Sandstone)	Hydrolyzates (Shale)	Precipitates (Carbonates)
Si	285,000	359,000	260,000	34
Al	79,500	32,100	80,100	8,970
Fe	42,200	18,600	38,800	8,190
Ca	36,200	22,400	22,500	272,000
Na	28,100	3,870	4,850	393
K	25,700	13,200	24,900	2,390
Mg	17,600	8,100	16,400	45,300
Ti	4,830	1,950	4,440	377
P	1,100	539	733	281
Mn	937	392	575	842
F	715	220	560	112
Ba	595	193	250	30
S	410	945	1,850	4,550
Sr	368	28	290	617
C	320	13,800	15,300	113,500
Cl	305	15	170	305
Cr	198	120	423	7.1
Rb	166	197	243	46
Zr	160	204	142	18
V	149	20	101	13
Ce	130	55	45	11
Cu	97	15	45	4.4
Ni	94	2.6	29	13
Zn	80	16	130	16
Nd	56	24	18	8.0
La	48	19	28	9.4
N	46	----------	600	----------
Y	41	16	20	15
Li	32	15	46	5.2
Co	23	.33	8.1	.12
Nb	20	.096	20	.44
Ga	18	5.9	23	2.7
Pr	17	7.0	5.5	1.3
Pb	16	14	80	16
Sm	16	6.6	5.0	1.1
Sc	15	.73	10	.68
Th	11	3.9	13	.20
Gd	9.9	4.4	4.1	.77
Dy	9.8	3.1	4.2	.53
B	7.5	90	194	16
Yb	4.8	1.6	1.6	.20
Cs	4.3	2.2	6.2	.77
Hf	3.9	3.0	3.1	.23
Be	3.6	.26	2.1	.18
Er	3.6	.88	1.8	.45
U	2.8	1.0	4.5	2.2
Sn	2.5	.12	4.1	.17
Ho	2.4	1.1	.82	.18
Br	2.4	1.0	4.3	6.6
Eu	2.3	.94	1.1	.19
Ta	2.0	.10	3.5	.10
Tb	1.8	.74	.54	.14
As	1.8	1.0	9.0	1.8
W	1.4	1.6	1.9	.56
Ge	1.4	.88	1.3	.036
Mo	1.2	.50	4.2	.75
Lu	1.1	.30	.28	.11
Tl	1.1	1.5	1.6	.065
Tm	.94	.30	.29	.075
Sb	.81	.014	.81	.20
I	.45	4.4	3.8	1.6
Hg	.33	.057	.27	.046
Cd	.19	.020	.18	.048
In	.19	.13	.22	.068
Ag	.15	.12	.27	.19
Se	.050	.52	.60	.32
Au	.0036	.0046	.0034	.0018

FIG.7 The average composition of igneous and sedimentary rocks, in parts per million (Hem, pg.7).

decomposition of the sediment may occur at a more accelerated rate than that of the original rock, because of the increased surface area of the fragments.

Consolidated resistate sediments, such as sandstone, are also subject to attack by aqueous solutions. The cement binding the sand grains together may have been deposited by earlier waters circulating around the grains. As a result, this cement may be subject to dissolution (Hem, 1970). Common cements include calcium carbonate, silica, ferric hydroxide, ferrous carbonate, and clay minerals.

Many resistate sedimentary rocks are somewhat permeable to aqueous solutions, and therefore alteration of the rocks may occur. One type of alteration, described above, is the redissolving and reprecipitation of the cementing material.

A second type of alteration is adsorption and ion exchange (Hem, 1970). Most minerals have some cation-exchange capability, while some even possess anion-exchange capability. There is always an ion present at the site of exchange. An ion from an aqueous solution can be adsorbed at the mineral surface while the sorbed ion at the site is released into solution.

Adsorption simply means that the surface of a solid, in contact with a gas or liquid, is covered with a fine layer of tightly held ions or molecules removed from the nonsolid phase. Ion exchange refers to the replacement of these adsorbed ions by ions from the aqueous solution (Hem, 1970).

In natural water, adsorption involves the forces of chemical bonding and is thus referred to as chemisorption. (Hem, 1970). The capability of a solid for chemisorption is dependent upon the

chemical bonding within the mineral structure.

Usually there is an excess of negative charges within the crystal lattice of the exchange media, in this case, the solid surface of the mineral. Because of the excess of negative charges, positive ions are attracted to those sites. Usually, divalent cations are more strongly adsorbed, than monovalent cations (Hem, 1970).

Anion exchange may also occur if there is an excess of positive ions at the exchange site that would attract negative ions. The most abundant anions in natural water are bicarbonate (HCO3-) and sulfate (SO4=) ions (Hem, 1970).

Many resistate sediments exist in reducing environments for long periods of time. As a result, the mineral species comprising the sediment are also reduced. An example of this, and one of great concerns to the mining industry, is pyrite.

When water begins to circulate throughout the sediment it can cause oxidation and reduction reactions. Oxidation affects rocks lying above the water table and to a certain degree at greater depth, depending upon the availability of dissolved oxygen. Pyrite that was once stable in the reducing environment becomes readily oxidized with the influx of water.

The chemical composition of pyrite is FeS2. The sulfur in the pyrite is oxidized to the sulfate ion SO4=, and ferrous iron, Fe++, is released.

The second class of rock in the study area are hydrolyzates. The hydrolyzates are characterized by shales and other fine-grained material, composed mainly of clay minerals, that are

the result of chemical reactions between water and silicates.

Shales and other hydrolyzates are porous, but do not transmit water easily. The pore spaces are extremely small, poorly arranged, and often not interconnected.

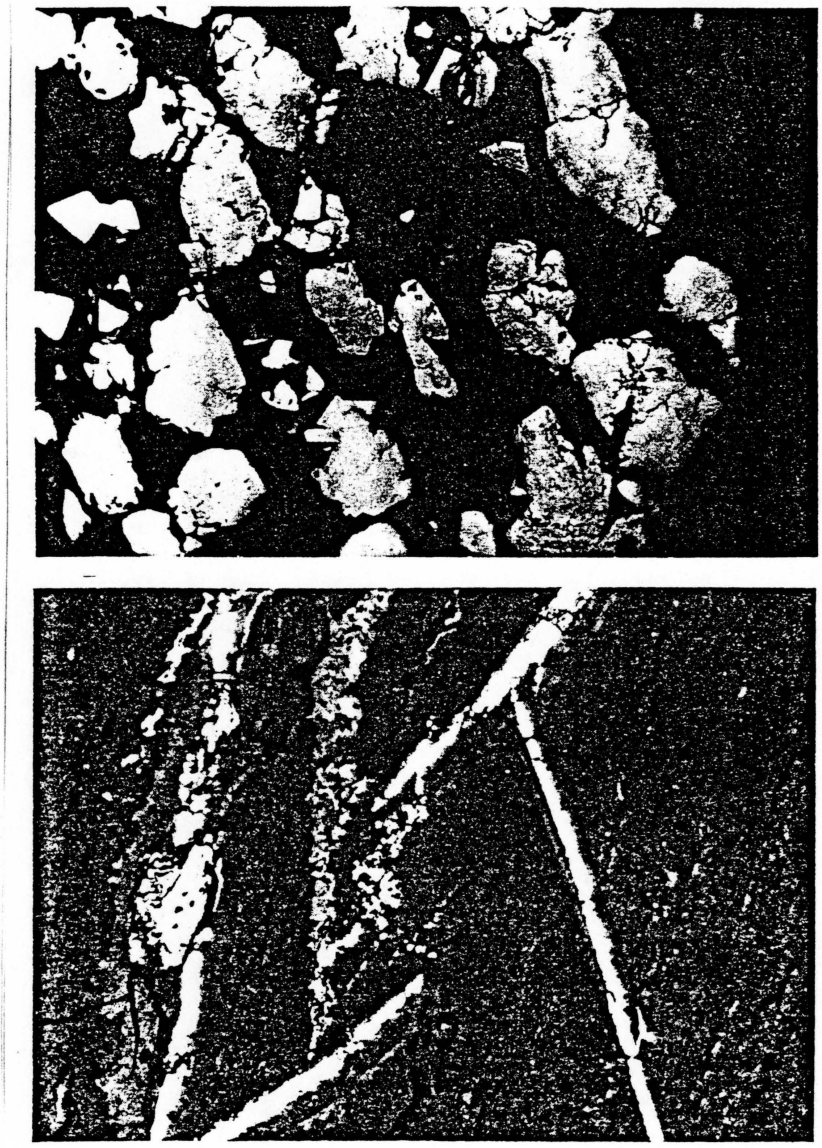
Shale, as an example, is often deposited under marine conditions. Many solutes, from the sea water, remain attached within the pore spaces of the shale long after deposition. Water circulating through an hydrolyzate may have a high concentration of dissolved solids due to these marine solutes. Pyrite and hydrolyzates are often found in association with one another (Hem, 1970).

Pyrite Oxidation

Pyrite may display three different types of structural morphology. Pyrite may be euhedral, where the crystal is completely bounded by its own regular crystal faces. For this type of structure the surface area is small, and therefore only a minimal amount of chemical reactions occur there. This form of pyrite is relatively inert.

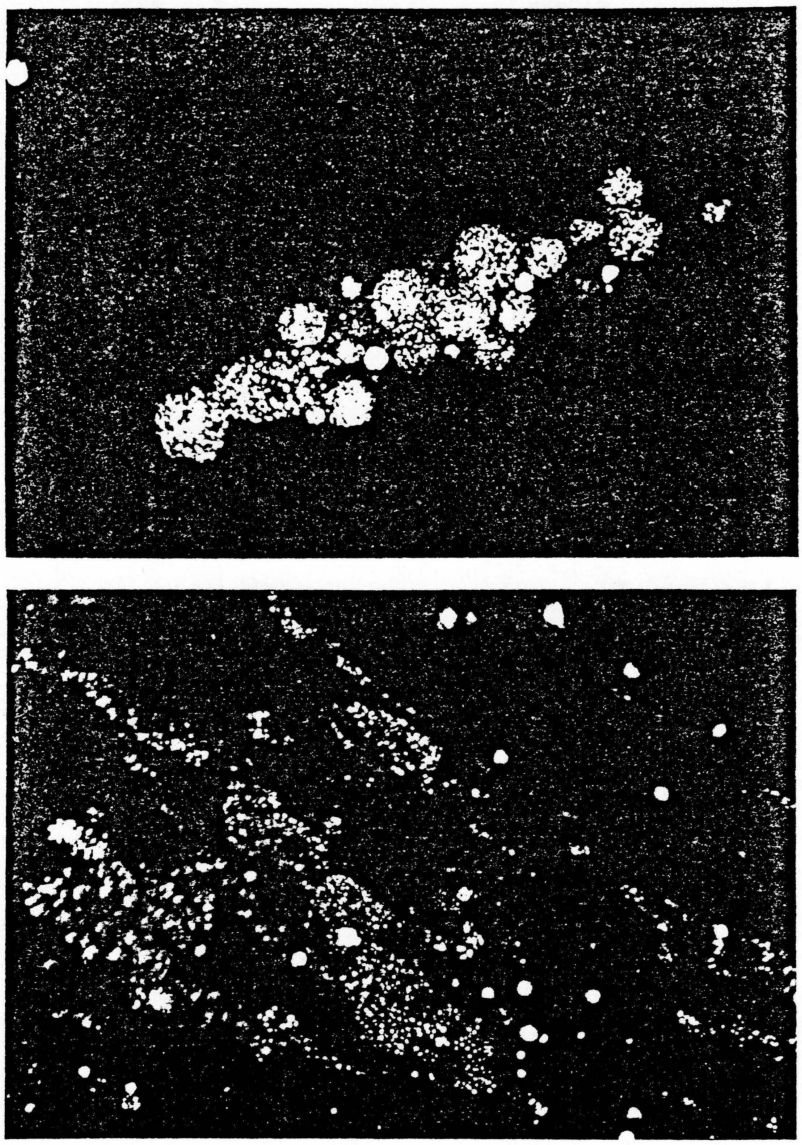
Massive pyrite displays no definite crystalline structure but does have slightly more surface area than the euhedral form and thus slightly greater reactivity.

The morphology of the pyrite represented in the strata within and surrounding the coal seams, in watershed 29 is framboidal. These crystals are microscopic spheroids, which are virtually impossible to remove from the overburden and the coal (see Figure 8a,b). The spheroids have an immense surface area, which promotes the acceleration of chemical reactions. The



Photomicrographs of stable pyrite (325×).

FIG.8a Photomicrograph of euhedral pyrite (Schaller and Sutton pg.130).



Photomicrographs of reactive pyrite (325×).

FIG.8b Photomicrograph of framboidal pyrite (Schaller and Sutton pg.131).

amount of reaction of the pyrite is directly proportional to its surface area since the chemical reaction site is the pyrite surface. Consequently, the surface environment of the pyrite will determine the rate of the reaction (Schaller and Sutton, 1978).

Three basic equations represent the chemical processes involved in the production of acid drainage. They are as follow:

I. $FeS2\ (s) + 3\ 1/2\ O2 + H2O \longrightarrow 2SO4= + Fe{+}{+} + 2H+$

II. $Fe{+}{+} + 1/4\ O2 + H+ \longrightarrow Fe{+}{+}{+} + 1/2\ H2O$

III. $Fe{+}{+}{+} + 3H2O \longrightarrow Fe(OH)3\downarrow + 3H+$

(OSU, 1971).

The final products of these reactions are acid and ferric hydroxide. Acid mine water is a complex mixture of metallic ions. In equation I, 1 mole of FeS2 will produce 2 moles of H+ ion (acidity). In addition, when the Fe++ ion is oxidized to Fe+++ ion, 3 more moles of H+ ion are produced.

Equation I represents the initial oxidation reaction at the pyrite surface. The rate of the reaction is controlled by conditions on the pyrite surface, which include the oxygen concentration and the pyrite morphology. In general, the rate of the reaction is dependent upon the concentration of the reactants at the site of the reaction (OSU, 1971).

Equation I is a mixture of chemical phases. It involves pyrite, a solid crystalline, oxygen, either in the gas phase or dissolved in water, and water, which can be in the liquid or vapor phase.

In equation I, the system is not in equilibrium in a mined

area. The exposed pyrite is continuously being oxidized. The rate of the oxidation thus determines the magnitude of the acid production.

Two oxidizing agents in nature are oxygen and ferric iron. Both are electron acceptors in the oxidation of pyrite, but oxygen is the key agent in the oxidation process.

Oxygen can be in the gaseous state or dissolved in an aqueous solution. The amount of oxygen dissolved in water is insignificant in the oxidation of pyrite. Therefore, the oxygen reacting with the pyrite must enter the system as a gas. Pyrite that is covered by 1-2cm of water is effectively shielded from the atmospheric oxygen. This is due to the slow rate of diffusion of oxygen into water. If the film of water on the reaction site is less than 1cm, then the diffusion of the oxygen is somewhat hindered. The products of oxidation will eventually be transported away from the reaction site in the form of seepage (OSU, 1971).

When the pyrite is oxidized, ferrous iron is released. The ferrous iron can then be oxidized to ferric iron. Drainage close to the site of the pyrite oxidation is not likely to contain iron in the form of Fe+++. This is due to the slow rate of Fe++ oxidation in an acid solution and the rapid rate of reduction of Fe+++ at the pyrite surface (OSU, 1971).

When Fe++ ions are transported from the reaction site, they mix with ground water. As a result, the pH of the water can be raised slightly and the rate of oxidation of Fe++ to Fe+++ may be greatly enhanced.

In underground mines, bacteria grows profusely in pooled water that is exposed to oxygen. The bacteria can act as a catalyst for the oxidation of the iron. Therefore, almost total conversion of Fe++ to Fe+++ may occur before the drainage water leaves the mine (OSU, 1971).

The third equation (III) forms an iron hydroxide precipitate referred to as "yellow boy" precipitate. This reaction depends on the concentration of the ferrous iron and the pH of the water. As the pH approaches neutrality, the reaction becomes more complete (OSU, 1971).

Both equations II and III may begin at the site of oxidation on the pyrite surface. Neither reaction will continue to any degree until the acid drainage water is diluted with ground water. This results in a gradual increase in the pH of the water to near-neutrality.

Parameters

Selection

The parameters selected for testing, were chosen on the basis of the types of reactions occurring in coal mined areas. The common constituents of drainage waters from mines are hydrogen ions and iron hydroxides.

The three major sources for hydrogen ions are:

a) hydrolysis: $H2O \longrightarrow H+ + OH-$

b) dissociation of acidic solutes: $H2CO3 \longrightarrow H+ + HCO3-$

c) oxidation: $H2S + 4H2O \longrightarrow SO4= + 10H+ + 8e-$

(Hem, 1970).

Oxidation, the major reaction occurring in acid-mine drainage,

established the range of parameters to be considered, along with several other constituents normally examined in acid mine water.

The eight parameters selected for laboratory testing were alkalinity, acidity, pH, conductivity, and the concentrations of sulfate, iron, manganese, and total nonfiltrable residue.

Description

Standards described in the following sections are based upon acceptable levels established by the U.S. Public Health Service for drinking water and aquatic life.

Alkalinity and Acidity

By definition, alkalinity is the content of negative ions or other substances that react to neutralize hydrogen ions added in titration with an acid (Camp and Meserve, 1974). This simply means that alkalinity is a measure of the water's capacity to neutralize an acid.

The result is that alkalinity indicates the presence of carbonates, bicarbonates, and hydroxides in the water.

Alkalinity and acidity are affected by H+ ion concentrations, mineral composition, water temperature, and ionic strength (McNee and Neimanis, 1978). They also vary with the discharge of the stream. High alkalinity usually occurs with low discharge.

In natural surface waters, the alkalinity is usually less than 500 mg/l. An acceptable range for drinking water is 30-500 mg/l (McNeely and Neimanis, 1978).

High alkalinity indicates excessive hardness of the water or

a high concentration of sodium salts. Low alkalinity means the acid content in the water is reasonably high. This could result in the corrosion of pipes and plumbing.

Acidity, is the capacity of an aqueous solution to react with, and neutralize hydroxyl ions. Acidity is usually due to the presence of mineral acids or hydrolyzable salts of mineral acids. In natural water an equilibrium exists between carbonate, bicarbonate, and carbon dioxide. When acid pollutants are introduced into the system the equilibrium is upset.

pH

pH is a measure of the hydrogen ion concentration in solution. It indicates whether or not a balance exists between the acids and bases in solution. It is also an indicator of the solvent power of the water, therefore the chemical reactivity of the water with rocks and soil can be predicted.

The hydrogen ion concentration is measured on an exponential scale from 0-14, with 7 being neutral. Natural surface waters range in pH from 6.5-9, with most surface waters tending to be slightly basic. Increased acidity will indicate the presence of mineral acids and carbonic acids while an increase in basicity indicates the presence of carbonate, bicarbonate, and hydroxide ions. The hydrogen ion content of the water does not become a major component of the solution until the pH is less than 4.

Drinking water standards have established an acceptable pH range of 6.5-8.3. Aquatic life standards are slightly higher, with pH of 6.5-9 (McNeely and Neimanis, 1978).

The oxidation of pyrite definitely affects the pH of the

water. $Fe^{+++} + 3H_2O \longrightarrow Fe(OH)_3 + 3H^+$. Although an iron hydroxide precipitate is formed hydrogen ions are released, increasing the hydrogen ion concentration which in turn lowers the pH.

II. $FeS_2 (s) + 8H_2O \longrightarrow Fe^{++} + 2SO_4^{=} + 16H^+ + 14e^-$. In the oxidation of pyrite, atmospheric oxygen acts as the reducing agent, and the sulfur is oxidized. As a consequence, hydrogen ions are once again released, and the pH is lowered.

Conductivity

Specific conductance is the numercial expression of a solution's ability to conduct an electrical current (McNeely and Neimanis, 1978). Conductivity is dependent upon ionic concentration and temperature. If the ionic concentration increases, then the specific conductance will also increase. Therefore, conductivity is an indicator of the ion concentration (see Figures 9 and 10). Conductivity is sensitive to variations in mineral compositions of the water, but it cannot indicate variations in the quantities of the dissolved solids.

Hem states "To conduct a current, solute ions must move through the solution to transfer charges, and the effectiveness of a particular ion in this process depends upon its charge, size, the way it interacts with the solvent, and other factors." The mobility of the ions is a measure of the velocity of an ion in a potential gradient of one volt per centimeter (Hem, 1970). The unit of measure, mhos, is the reciprocal of ohms, which measures resistance.

The range for conductivity of natural water is 50-1500 umhos. For agricultural uses, such as irrigation, conductivities

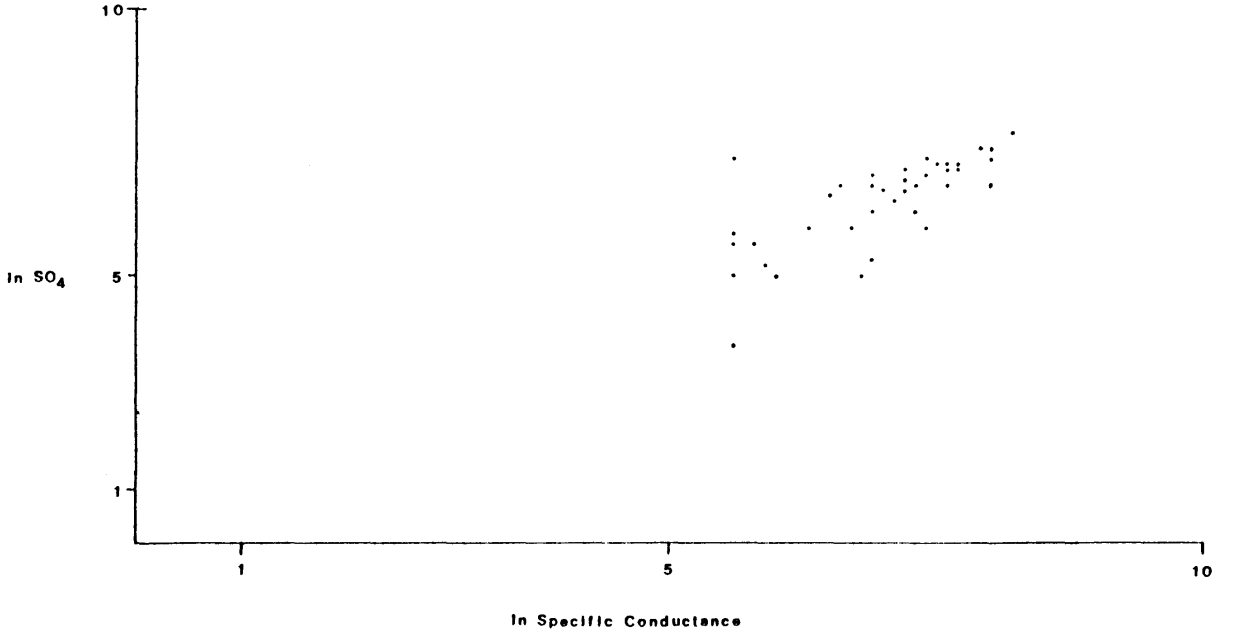


Fig. 9 Sulfate concentrations, collected in the study area, tend to increase with increasing specific conductance on a natural logarithmic scale.

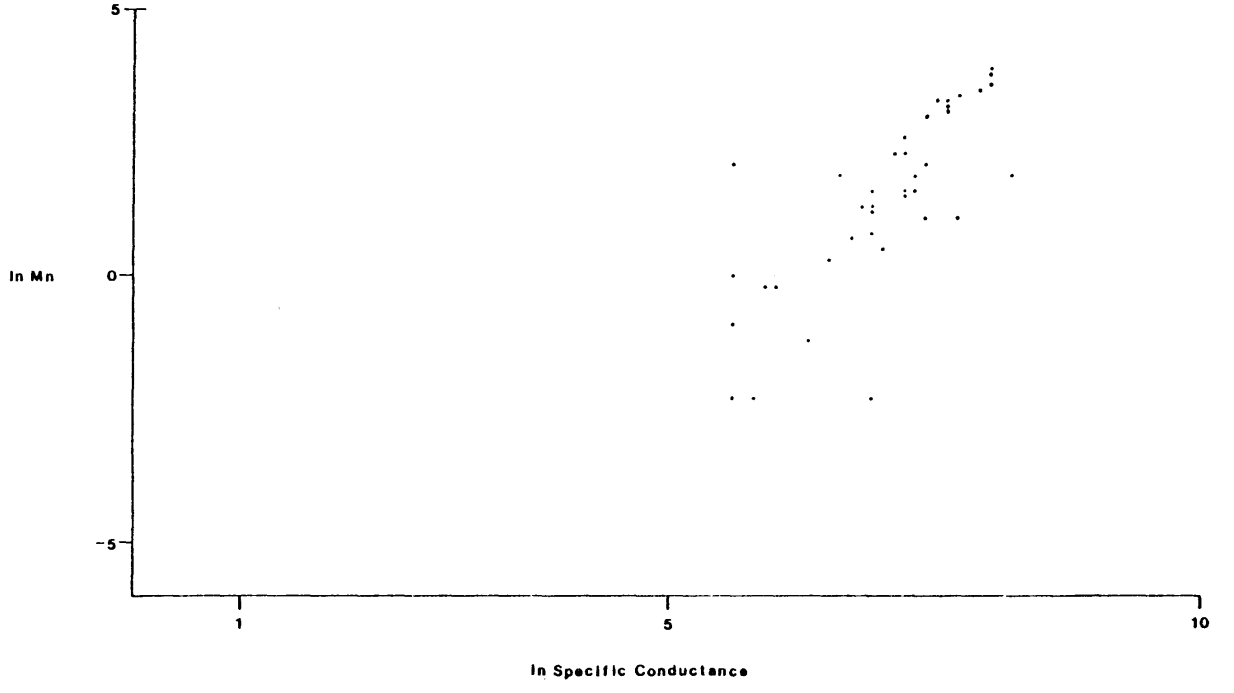


Fig. 10 Manganese concentrations, from the study area, increase with increasing specific conductance on a natural logarithmic scale.

usually range below 750 umhos. Values may range as high as 2250 umhos, but saline conditions will soon develop if leaching and drainage are not adequate (Camp and Meserve, 1974).

No strict guidelines have been established for specific conductance because of the direct relationship of conductivity to the total dissolved solids. The components comprising total dissolved solids already have restrictions placed upon them.

Sulfate

Sulfate, SO4=, is the stable, highly oxidized state of sulfur, that is readily soluble in water. In natural water, it varies in concentration from a few mg/l to 1000 mg/l. Sulfate is derived from the weathering of shale and most sedimentary rocks. The most appreciable quantities are oxidized from gypsum and anhydrite.

A moderately high concentration is considered to be 200-300 mg/l. Drinking water standards are usually set at 250 mg/l, however, levels up to 500 mg/l are permissable. Concentrations for water of livestock are allowed as high as 1000 mg/l. Sulfate, in natural water, seldom reaches concentrations high enough to affect aquatic life (McNeely and Neimanis, 1978).

Sulfate in the water will contribute to the hardness, corrosivity of metals, and taste, due to salinity.

Iron

Iron is the fourth most abundant element in the earth's crust. It exists in two forms; the ferrous state, Fe++, and the ferric state, Fe+++.

Ferrous iron is present and mobile in water that is under

reducing conditions. When the ferrous iron is exposed to the atmosphere, it is oxidized, becomes less mobile, and eventually precipitates out as ferric iron. As a result, it produces a reddish-brown stain in water.

Major sources of iron are minerals of igneous rocks, such as amphiboles, ferro-magnesian micas, magnetite, iron pyrite, and marcasite (Hem, 1970). Iron found in sedimentary rocks include, carbonates, iron sulfides, and clay minerals. Iron found in igneous rocks is usually in the ferrous form, but it can be mixed with ferric iron. The iron is also in the ferrous form in sediments. Iron oxides and hydroxides can be leached from sandstone (Studlick, 1977).

The concentration of iron in aerated surface water is usually less than 0.5 mg/l. Ground water with a pH less than 8 may contain up to 10 mg/l of iron. Acid water from thermal springs, industrial wastes, and mine wastes have reached concentrations greater than 6000 mg/l (McNeely and Neimanis, 1978).

Iron is objectionable in drinking water because it gives the water a bitter-sweet astringent taste. Established drinking water standards for iron permit concentrations no greater than 0.3 mg/l. For taste, however, the level should not exceed 0.05 mg/l. The 0.3 mg/l is also the maximum level for the protection of aquatic life. In small quantities iron can be a minor plant nutrient, but toxicity has been recorded at concentrations greater than 20 mg/l (McNeely and Neimanis, 1978).

Manganese

Manganese is a metallic cation that displays the same chemical behavior as iron. It is often found in association with iron. Manganese may exist in the Mn++ state or it can readily be oxidized to the Mn++++ state, where it will precipitate out. The salts of manganese such as MnNO3, MnSO4, and MnCl2 are very soluble in water, unlike the oxides and hydroxides of manganese (Hem, 1970).

The major sources of dissolved manganese are soil, and metamorphic and sedimentary rocks. The largest contributors of manganese are the ferro-magnesian minerals such as biotite and hornblende (Studlick, 1977).

In surface waters, manganese is usually not abundant. It seldom reaches concentrations greater than 1.0 mg/l and concentrations are usually less than 0.2 mg/l. The standard level of manganese permissable for drinking water is 0.05 mg/l, which is also the maximum level allowed for aquatic life. Some acidic waters amy reach levels of 10 mg/l. If the water contains greater than 0.2 mg/l of manganese, it will acquire an undesirable taste and become stained (McNeely and Neimanis, 1978).

Turbidity

The total nonfiltrable residue or the turbidity of a solution is the measure of the quantity of suspended particles in that solution. This includes silt, clay, organic matter, plankton, and microscopic organisms. These suspended particles may also be referred to as colloidal particles (McNeely and Neimanis, 1978).

Glasstone and Lewis define the range of sizes for colloidal particles. Under their classification, the diameter can vary from approximately 5.0 millimicrons to 0.2 microns (1 micron = 0.0001cm = 10000 A°). The lower limit of the diameter of the colloidal particle is 50 A° (Hem, 1970).

Turbidity is actually the capacity of water for absorbing or scattering light. It is measured by determining the concentration for fine silica that produce the same effect (Hem, 1970). Turbidity is dependent upon the size, character, and concentration of the particles.

The sources of suspended particles are usually erosion, runoff, and algal blooms. Turbidity does not have an affect on the quality of drinking water. However, it is usually limited to 500 mg/l. Turbidity can affect aquatic life. High turbidity will reduce the photosynthetic process of submerged aquatic plants. This results in a reduction of plant growth which in turn may lead to a reduction in the fish population that feed upon these plants (McNeely and Neimanis, 1978).

Results of Data

Conclusions drawn from the data collected at high flow in the study area have been based primarily on standards established for drinking water by the U.S. Public Health Service (see Figure 11).

The highest acidity recorded is 2408 mg/l, with a corresponding alkalinity of 0 mg/l and a pH of 2.5. This analysis is for sample 13, which is a small tributary into Dry Run from the north. Thick dark reddish-orange sediment lines the

U.S. Public Health Service Drinking Water Standards

Substance	Concentration (mg/liter)
Alkyl benzene sulfonate (ABS)	0.5
Arsenic (As)	0.01
Chloride (Cl)	250.0
Copper (Cu)	1.0
Carbon chloroform extract (CCE)	0.2
Cyanide (CN)	0.01
Fluoride (F)	(See 5.2.3)
Iron (Fe)	0.3
Manganese (Mn)	0.05
Nitrate[a] (NO_3)	45.0
Phenols	0.001
Sulfate (SO_4)	250.0
Total dissolved solids	500.0
Zinc (Zn)	5.0

[a]In areas in which the nitrate content of water is known to be in excess of the listed concentration, the public should be warned of the potential dangers of using the water for infant feeding.

FIG.11 Acceptable drinking water standards established by the U.S. Public Health Service (McNeely and Neimanis, 1978).

stream banks, while dark green algae covers the stream bottom. Abundant amounts of coal and shale lie exposed in piles nearby the stream. Vegetation is absent in and around the stream.

Sample site 13 also has the highest sulfate and iron concentrations. These values are 2150 mg/l and 525 mg/l, respectively. The highest conductivity is also recorded at site 13 as 3500 umhos/cm.

The highest manganese concentration is from sample site 19, with a value of 50 mg/l. The highest concentration of nonfiltrable solids, 148 mg/l, is also from sample site 19. Table 3 compares the average for the two metallic ions, the sulfate salt, and the pH with drinking water standards established by the U.S. Public Health Service. In all four cases, the water quality is far below the standards established for drinking water (see the Appendix, Table 5 for a complete listing of the samples and their corresponding values).

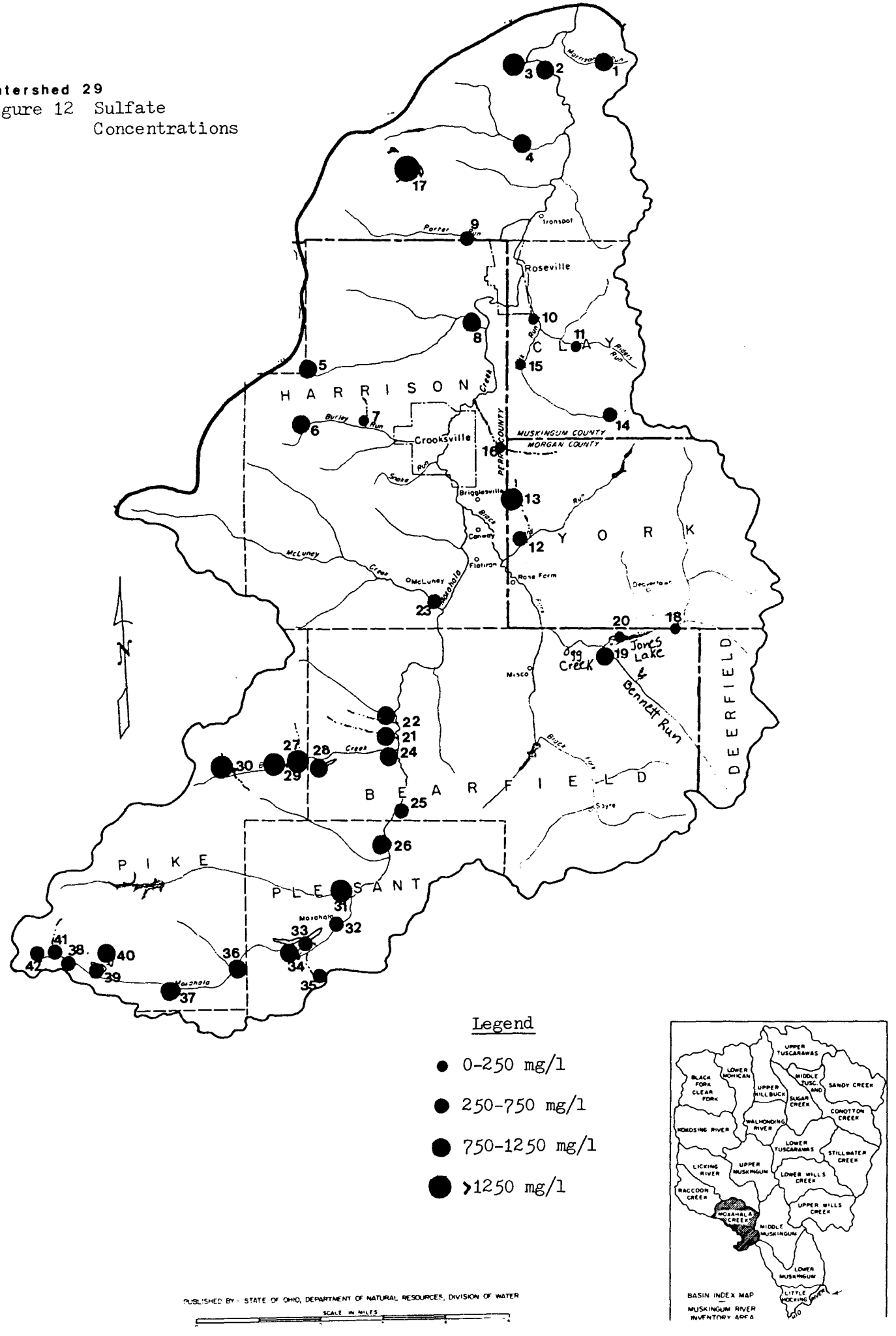
In general, the more highly toxic streams are located in the west-southwestern portion of the waterhed. The less disturbed streams lie in the east-northeast. Figures 12, 13, and 14 show the varying concentrations of sulfate, iron, and manganese throughout the watershed. The higher concentrations of the dissolved ions appear to congregate in the middle to southern portion of the watershed. A great deal of mining has been done in the southern portion of the study area and many underground mines are located there. The presence of both surface and subsurface mining in this area is one explanation as to why the streams are more highly acidic there.

The chemical results from site 13, located on the

Parameter	Average of Sample (mg/l)	Standard (mg/l)
SO_4	820	250
Fe	38.8	0.3
Mn	12.8	0.05
pH	4.48	6.5-8.3

Table 3 Comparison of sample concentrations with acceptable standard concentrations for drinking water.

Watershed 29
Figure 12 Sulfate Concentrations



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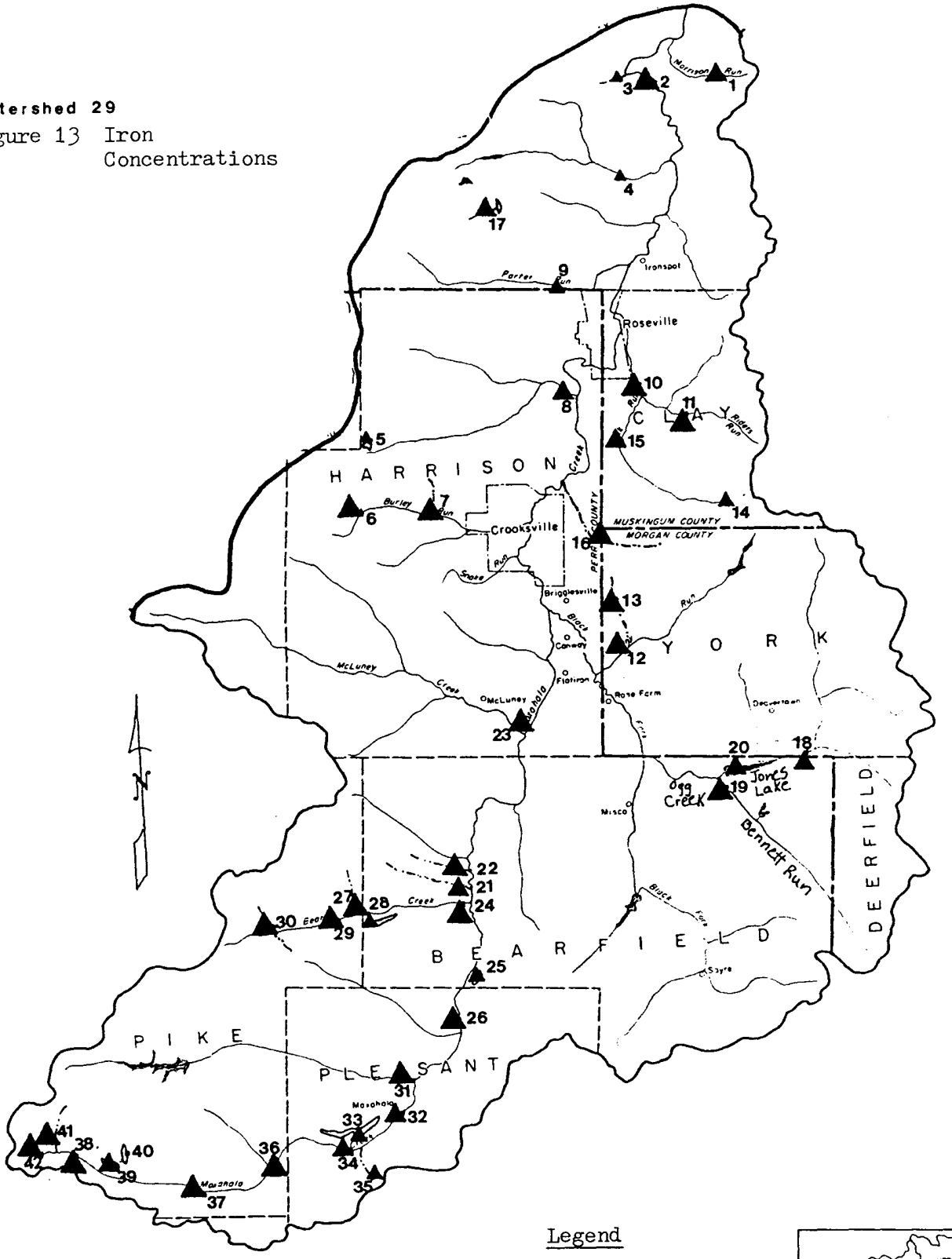
SCALE IN MILES

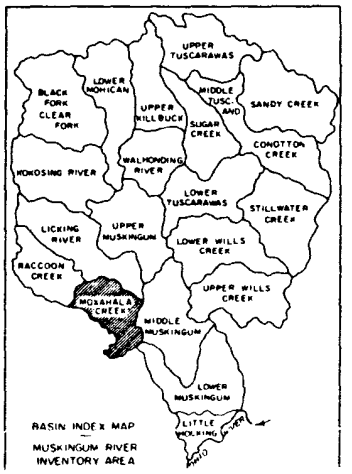
Watershed 29

Figure 13 Iron Concentrations



Legend

- ▲ 0-0.3 mg/l
- ▲ 0.3-1.0 mg/l
- ▲ 1.0-10.0 mg/l
- ▲ >10.0 mg/l



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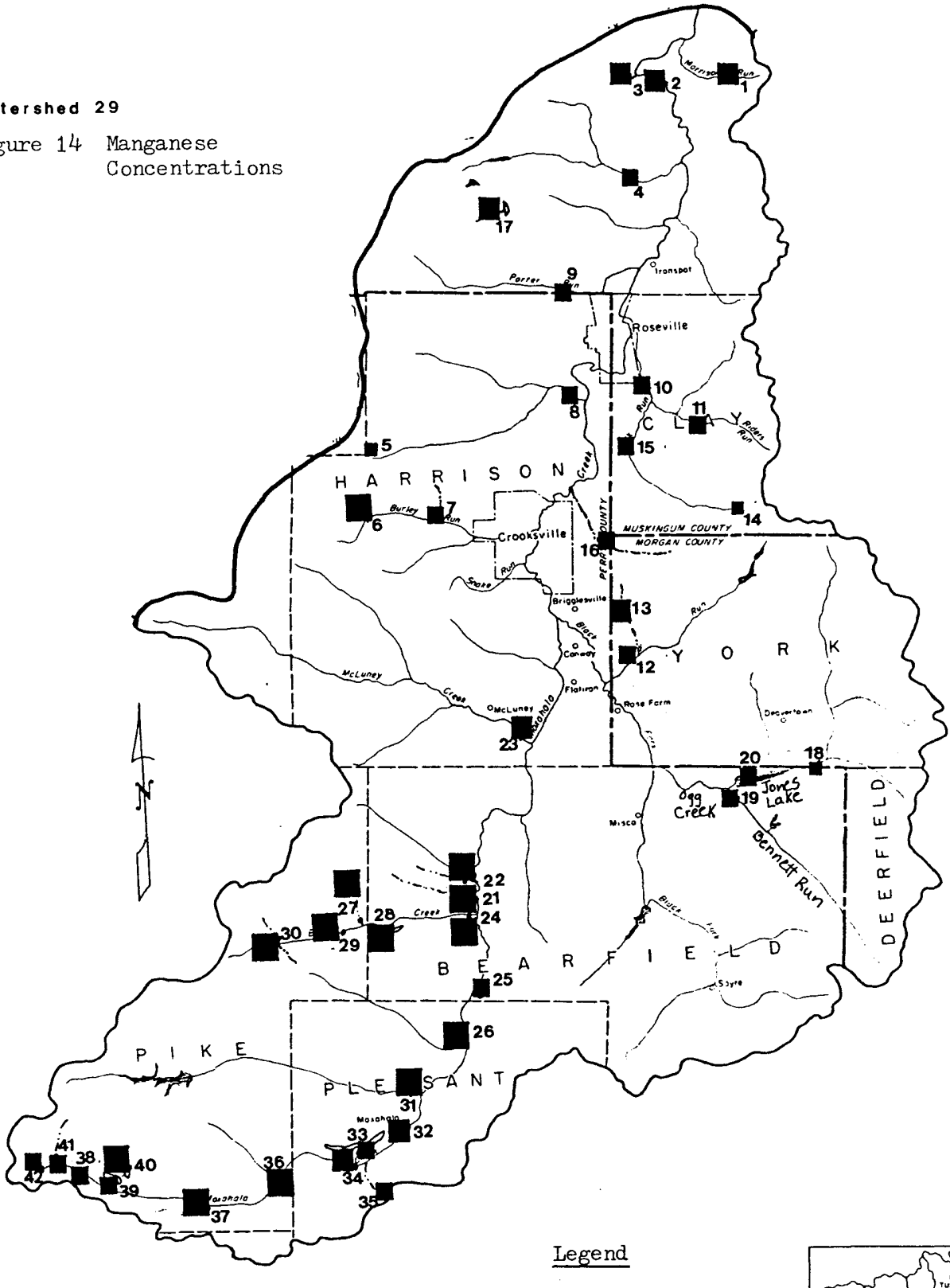
SCALE IN MILES

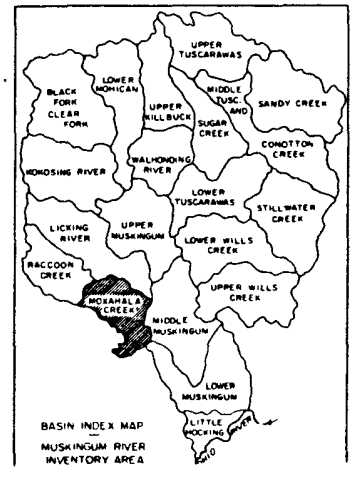
Watershed 29

Figure 14 Manganese Concentrations



Legend

- ■ < 0.1 mg/l
- ■ 0.1-5.0 mg/l
- ■ 5.0-20.0 mg/l
- ■ > 20.0 mg/l



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SCALE IN MILES

Crooksville quadrangle, initially appear to be anomalous. The 1975 topographic map does not indicate any type of surface mining within a radius of approximately 0.5 miles of the site. However, after consulting the O'Neil map of area 15 (see Figure 15) which displays all underground mining operations, site 13 is located directly above mine 298, in section 22. This may explain why site 13 has the poorest quality water, out of the 42 sampled sites.

Quadrangle maps of Fultonham and New Lexington are the only available maps of abandoned underground mines. When comparing the parameters of samples taken in surface mined areas to those taken near drift entries, the quality of the surface mined samples appear to be poorer. The underground mine samples are toxic, but their quality is not as low as the surface mined samples. Eight samples, 27, 28, 29, 32, 38, 39, 41, and 42 are taken in the vicinity of a drift entry.

One explanation for the difference in water quality between surface and subsurface mines, can be seen on the O'Neil map of underground mines. The entire watershed is underlain by extensive underground mines. In many areas the surface has been removed directly above, or adjacent to an underground mine. Consequently, subsurface mining, along with surface mining, has compounded the toxic waste problem. The acid production from these areas is greatly magnified compared to the production from an underground mine alone.

Conclusion and Summary

The portion of the Moxahala drainage basin, which includes

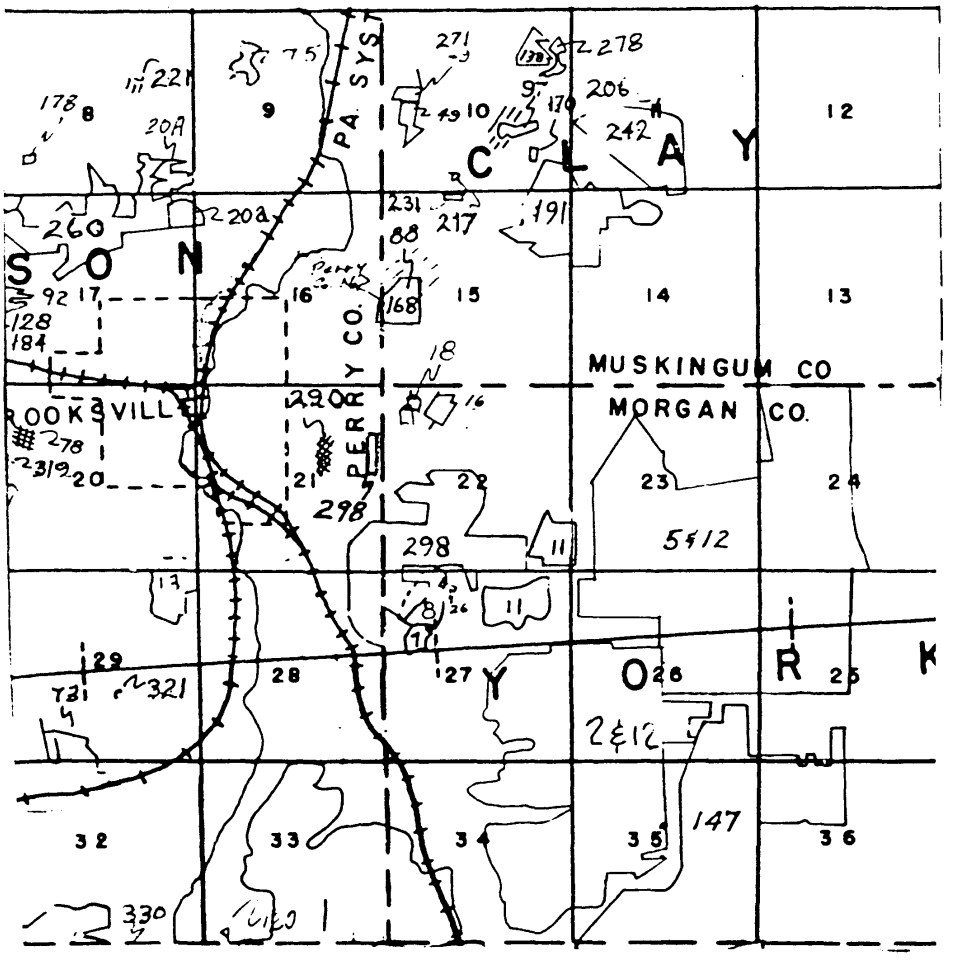


FIG.15 O'Neil map of area 15, containing sample site 13 in section 22.

watershed 29, is disturbed by acid drainage from local surface mines. The water is unsuitable for aquatic life, with the exception of the dark green algae, which appears to thrive in this type of environment. Vegetation is sparse to nonexistant along stream channels. In many areas, stream channels are so heavily covered with sediment, that the flow of water has dwindled to a mere trickle.

In surface mined areas, many closed basins along high walls have been left behind once mining operations ceased. Runoff into these basins is trapped there. The only means of escape for the water is by evaporation or seepage. When evaporation occurs only the water is removed, and the acidic products remain concentrated in the basin.

Seepage from these basins is often one of the major contributors of acid into a stream flow. The resultant seepage into the nearby spoil banks causes the death of the vegetation located there.

A solution for the closed basin seepage problem might be to drain the toxic wastes from the basins and fill them in with nontoxic materials.

The acid concentration tends to vary somewhat with the discharge rates in the drainage system. In past investigations, it has been demonstrated that the acid flow rate (in lbs/day) tends to follow the trend of the stream flow rate. The concentration of the acid, (in mg/l) tends to vary inversely with the quantity of the stream flow. When the discharge increases, the acidic concentration tends to decrease.

In closed basins where the water collects, the pH of the

water tends to be lower in the autumn than in the spring. This is due in part to less precipitation in the autumn and therefore less dilution of the acid content in the water. There is also a higher evaporation rate in the late summer and early autumn compared to spring. As a result, more water evaporates out of the basins, leaving behind a higher concentration of acid.

Another problem is the presence of micro-organisms and bacteria that thrive in a highly acidic environment. Some organisms and bacteria consume pyrite as a nutrient and then excrete waste in the form of iron hydroxides and acid.

Some autotrophic bacteria can catalyze the oxidation reaction of pyrite when environmental conditions are favorable. One such group is Ferrobacillus-Thiobacillus. Both are sulfur-oxidizing bacteria (OSU, 1971).

There are also bacteria and micro-organisms capable of reducing sulfate to sulfide. The sulfide, in turn, reacts with available iron which results in an iron sulfide that precipitates out of solution. Consequently, some bacteria and micro-organisms may be quite beneficial in reducing the concentrations of sulfate and iron in solution.

Underground mines pose a special problem. The interior of the mines remain relatively humid throughout the year. The humidity is high enough to provide a constant source of moisture to the pyritic surface, thus insuring the continous production of acid. One measure taken to prevent this reaction is air sealing the mines. However, "breathing" of the semi-confined volume of gas within the mine occurs when there are fluctuations in the

atmospheric pressure (OSU, 1971).

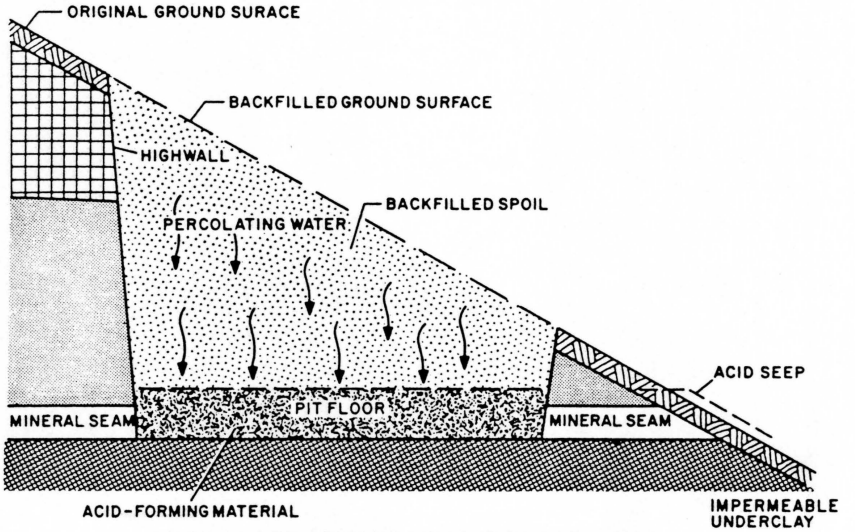
The bulkhead seals leak and the oxidation reaction continues. A more positive control for the problem is mine flooding. As a result, the reactive pyrite surface is concealed from the oxygen and acid production is abated.

In general, there are two types of controls which could be enforced to curtail the production of toxic wastes in this watershed. They are mass transport controls and kinetic reaction controls.

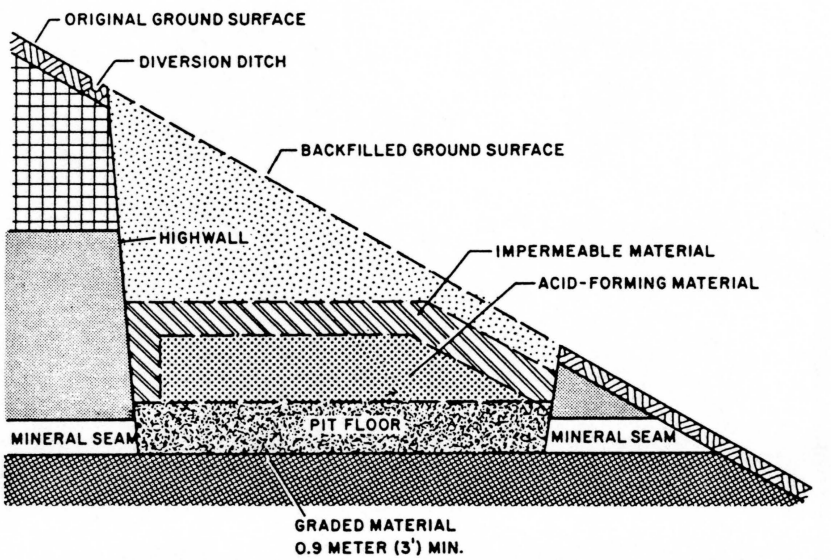
Mass transport can be abated at the oxidation reaction site if there is a control on the amount of water and oxygen available at the pyrite surface. This type of control is usually very costly and technically unfeasible. Another solution is to control the rate at which acid products are flushed out of the mined area and into the drainage systems. In watershed 29, the best methods of abatement would be to bury all exposed coal refuse and spoil piles and remove or fill in any standing pools of water in order to eliminate seepage through the spoil banks (see Figure 16). Finally, a sufficient growth of ground vegetation should be established to halt the massive erosion of sediments which chokes the stream channels.

Kinetic controls deal directly with the oxidation reaction at the pyrite surface. Introducing an inhibitor to the pyrite surface is one method of controlling the rate of oxidation. Where bacteria or micro-organisms act to catalyze the oxidation reaction, inhibitors can be introduced to prevent the catalyzing of the reaction (OSU, 1971).

Currently, acid drainage in watershed 29 is extensive and



POOR PLACEMENT RESULTING IN ACID SEEP.



PROPER PLACEMENT FOR ACID FORMING MATERIAL BURIAL

FIG.16 Cross-sectional view displaying the improper and proper placement of fill along a highwall (Schaller and Sutton, 1978).

severe. The methods of abatement discussed above have not been practiced. Both surface and underground mines have been abandoned, leaving behind spoil banks, coal refuse piles, toxic waste ponds, and other contributors to acid production. The only possibility for environmental recovery in the study area, is the abatement of sources contributing to acid mine drainage.

APPENDIX

Table 4 Sample Localities

Table 5 Water Quality

Method of determining percentages of underground mines

Generalized columnar section for Perry County, Ohio

Figure 17 General acid-production equations

Figure 18 Surface mining with concurrent reclamation

Figure 19 Conversion factors for water quality data

Figure 20 Guidelines

a) raw water
b) irrigation of acidic soils
c) food processing industries
d) electrical utilities
e) freshwater aquatic life

Table 4 Sample Localities

Sample	Location	Date	Time	Water Color	Temperature °C
1	Morrison Run	4-26-80	4:16 pm	orange	11
2	Moxahala Creek	4-26-80	4:44 pm	greenish yellow	11
3	tributary into Moxahala Creek	4-26-80	5:15 pm	grayish	11
4	tributary into Moxahala Creek	4-26-80	5:40 pm	bluish gray	11
5	small pond east of Saltillo	5-1-80	9:30 am	greenish	14
6	Burley Run	5-1-80	10:00 am	dark orange	12
7	tributary into Burley Run	5-1-80	10:20 am	orange	12
8	tributary into Moxahala Creek	5-1-80	10:45 am	orange	13
9	Porter Run	5-1-80	11:10 am	brown	14
10	Riders Run	5-1-80	11:30 am	orange	15
11	Riders Run	5-1-80	11:56 am	dark orange	16
12	Dry Run	5-1-80	12:46 pm	orange	19
13	tributary into Dry Run from the north	5-1-80	1:20 pm	dark orange	17
14	Elk Run	5-1-80	1:45 pm	brown	20
15	Elk Run	5-1-80	2:20 pm	tannish orange	22

Table 4 Sample Localities

Sample	Location	Date	Time	Water Color	Temperature °C
16	Possum Hollow	5-3-80	11:10 am	bright orange	16
17	small run into pond	5-4-80	1:50 pm	dark orange	24
18	Ogg Creek	5-4-80	2:45 pm	brown	21
19	Bennett Run	5-4-80	3:10 pm	orange	26
20	Jones Lake	5-4-80	4:10 pm	brown	23
21	tributary into Moxahala Creek	5-6-80	10:30 am	dark orange	16
22	tributary into Moxahala Creek	5-6-80	11:05 am	orange	17
23	McLuney Creek	5-6-80	11:35 am	orange	15
24	Bear Creek	5-6-80	12:20 pm	orange	17
25	pond in strip mine	5-6-80	1:10 pm	greenish blue	18
26	Moxahala Creek	5-6-80	1:45 pm	orange	18
27	tributary into Bear Creek	5-8-80	12:30 pm	orange	14
28	pond	5-8-80	1:00 pm	greenish yellow	16
29	Bear Creek	5-8-80	1:40 pm	dark orange	13
30	tributary into Bear Creek	5-8-80	2:05 pm	dark orange	14

Table 4 Sample Localities

Sample	Location	Date	Time	Water Color	Temperature °C
31	near gaging station #35	5-11-80	2:45 pm	dark orange	27
32	Moxahala Creek	5-11-80	3:10 pm	orange	20
33	pond along highwall	5-11-80	3:25 pm	greenish	19
34	Moxahala Creek	5-11-80	3:40 pm	orange	20
35	small run south of strip mine	5-11-80	3:55 pm	brown	20
36	Moxahala Creek	5-11-80	4:20 pm	bright orange	21
37	pond along along highwall	5-11-80	5:20 pm	orange	21
38	Moxahala Creek	5-11-80	6:10 pm	orange	22
39	pond along highwall	5-11-80	6:25 pm	greenish	19
40	pond along highwall	5-11-80	6:55 pm	orange	21
41	tributary into Moxahala Creek	5-11-80	7:20 pm	orange	17
42	tributary into Moxahala Creek	5-11-80	7:35 pm	orange	20

Table 5 Water Quality

Sample	Alkalinity mg/l	Acidity mg/l	Lab pH	Field pH	Conductivity μmhos/cm	Sulfate mg/l	Iron, Total mg/l	Manganese mg/l	Turbidity mg/l
1	0	83	3.83	3.8	760	775	3.6	6.8	8
2	0	173	3.25	3.2	1400	1050	15.0	10.0	36
3	14	0	7.39	5.3	1600	1400	0.3	8.4	15
4	12	6	6.54	5.7	1000	975	0.3	5.0	14
5	77	0	7.26	8.2	1000	850	<0.1	<0.1	3
6	0	239	3.15	2.9	1600	1025	11.0	21.0	3
7	0	140	3.44	3.4	880	150	12.0	3.8	53
8	0	50	4.32	4.2	1500	775	1.8	5.0	5
9	22	0	7.38	5.5	840	350	0.6	2.0	5
10	0	167	3.15	3.3	980	200	30.0	3.3	67
11	0	18	4.43	5.8	400	150	16.0	0.8	41
12	0	448	2.83	2.9	1600	350	62.0	3.1	113
13	0	2408	2.55	2.5	3500	2150	525.0	6.9	116
14	91	0	7.61	6.6	320	275	0.9	<0.1	15
15	31	11	6.81	6.4	350	175	2.4	0.8	9
16	0	252	3.17	3.5	980	200	38.0	2.3	73
17	0	124	3.41	3.6	270	1300	4.0	8.0	4
18	89	0	7.38	6.6	270	150	1.9	<0.1	4
19	0	1519	2.64	2.8	2200	1175	425.0	3.0	148

Table 5 Water Quality

Sample	Alkalinity mg/l	Acidity mg/l	Lab pH	Field pH	Conductivity μmhos/cm	Sulfate mg/l	Iron, Total mg/l	Manganese mg/l	Turbidity mg/l
20	102	0	7.29	6.5	280	40	3.1	1.0	62
21	22	8	6.59	5.6	2000	1200	8.3	26.0	11
22	0	105	3.28	3.7	2200	1050	26.0	30.5	29
23	0	320	3.08	3.0	1500	500	18.0	7.0	1
24	0	144	3.21	3.3	2300	1175	20.5	31.0	17
25	24	0	7.51	5.8	1300	725	0.6	5.0	1
26	0	281	3.02	3.0	2000	800	47.0	22.0	95
27	0	270	3.41	3.6	2900	1675	48.0	50.0	60
28	0	23	4.72	4.2	2100	1200	0.8	23.0	1
29	0	212	3.21	3.0	2900	1600	36.0	49.0	5
30	0	252	3.37	3.4	2900	1375	45.0	36.0	4
31	0	587	2.96	2.8	2800	1625	61.0	33.0	77
32	0	70	4.17	3.7	1200	625	2.4	10.0	9
33	49	0	7.40	6.0	560	350	0.4	0.3	8
34	0	108	3.57	3.2	1300	875	4.3	13.0	7
35	86	0	7.51	6.3	280	325	0.4	0.4	1
36	0	272	3.18	3.0	1900	1250	16.0	27.0	2
37	0	281	3.35	3.1	3000	800	16.0	46.0	18
38	0	196	3.11	3.0	1400	725	35.0	4.7	83

Table 5 Water Quality

Sample	Alkalinity mg/l	Acidity mg/l	Lab pH	Field pH	Conductivity μmhos/cm	Sulfate mg/l	Iron, Total mg/l	Manganese mg/l	Turbidity mg/l
39	0	83	3.53	3.3	1000	500	4.3	3.8	7
40	0	536	2.88	2.9	2000	1150	49.0	24.0	40
41	0	61	3.52	3.6	660	675	12.0	1.3	29
42	0	53	3.78	4.3	1100	725	24.0	1.6	55

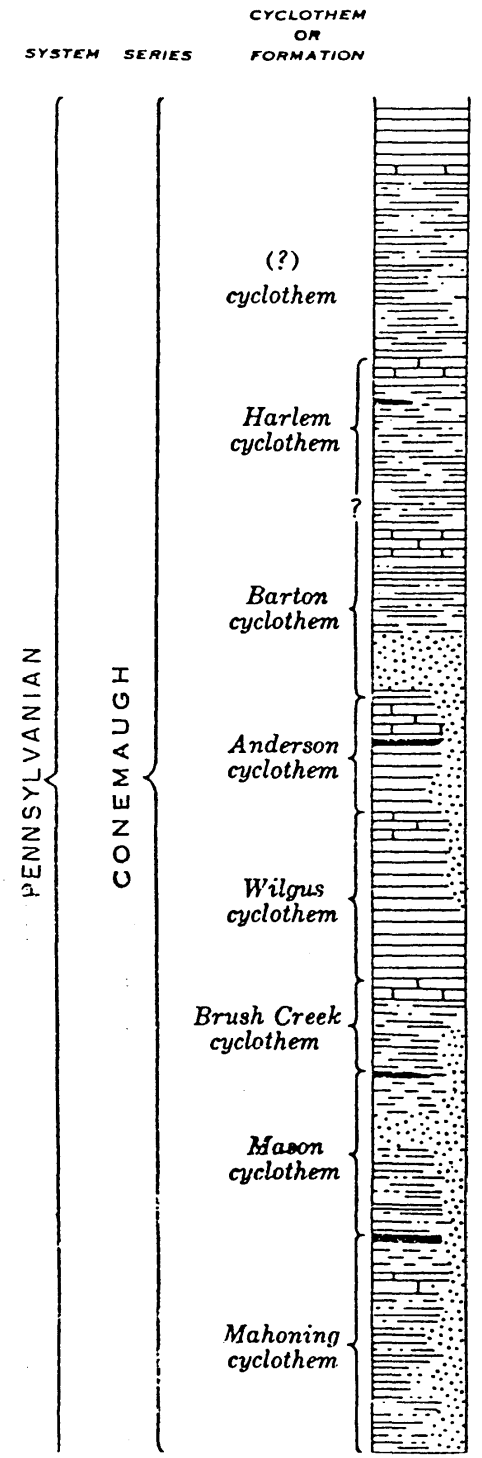
Method for determining percentages of underground mines

Computerized maps of watershed 29, located in Fultonham and New Lexington quadrangles, were overlain on corresponding quadrangle maps of abandoned underground mines. The boundaries of the underground mines were then traced onto the computerized maps. The number of cells were counted in each outlined area. The number of cells was converted into the area affected, using acres as the units. An average of 1.14 was used as the conversion factor. The conversion factor was obtained by taking the average of the number of acres divided by the number of cells per acre. The total number of acres was added for both quadrangles, and then divided by the total number of acres for each respective quadrangle. This resulted in the percentage of acreage involved in underground mining in both quadrangles.

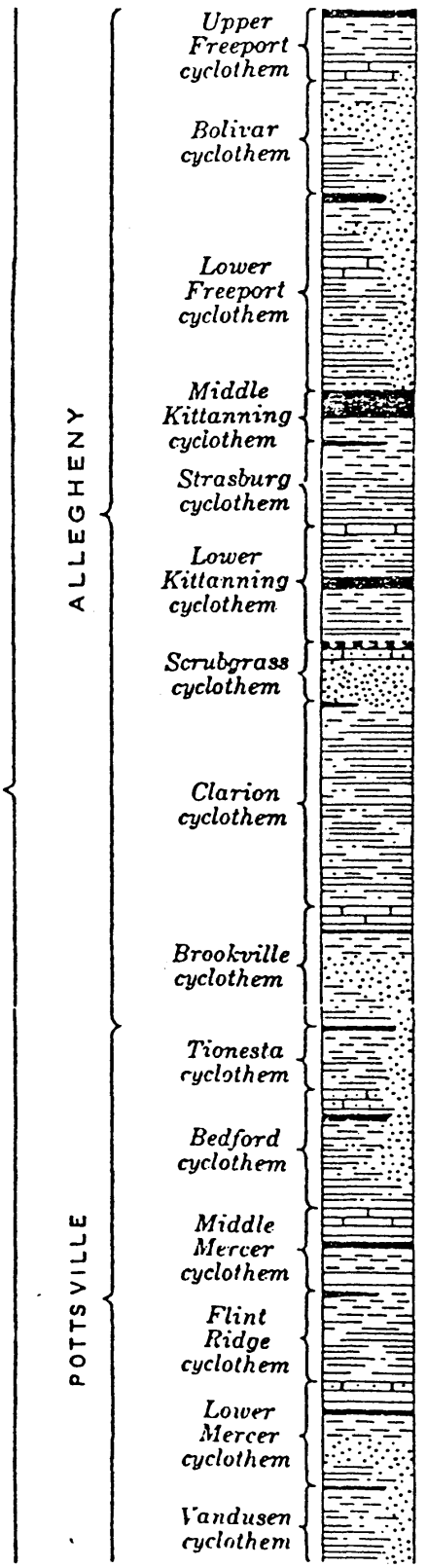
GENERALIZED COLUMNAR SECTION

STATE RECLAMATION LANDS

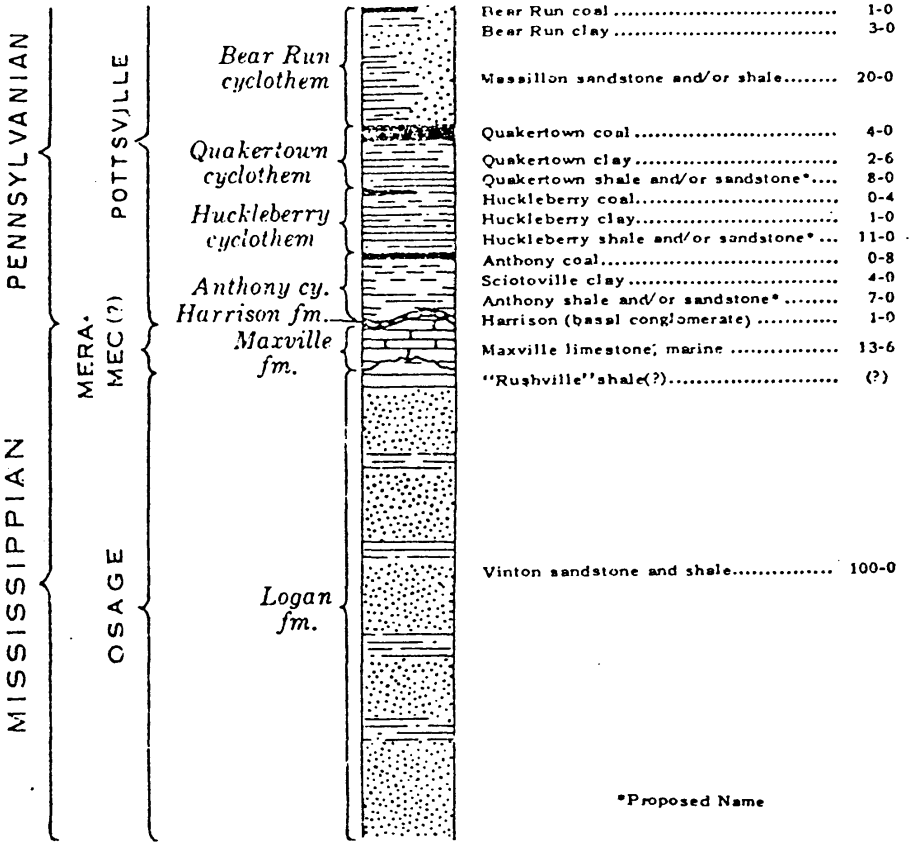
PERRY COUNTY, OHIO



MEMBER	AVERAGE THICKNESS Ft.-In.
(?) shale	10-0
(?) limestone	1-0
(?) shale	40-0
Ames limestone, marine	1-9
Unnamed shale	2-0
Harlem coal	0-4
Harlem clay	1-0
Harlem shale and /or sandstone	25-0
(Barton coal absent)	
Ewing limestone	4-6
Cow Run shale and /or sandstone	30-0
Portersville marine shale and limestone	4-6
Anderson coal	1-0
(Bloomfield limestone absent)	
Anderson shale*	15-0
Cambridge limestone, nodular, marine	1-9
(Wilgus clay and coal absent)	
Buffalo shale	33-0
Brush Creek limestone, marine	2-3
(Brush Creek clay and coal absent)	
Brush Creek shale*	17-0
Mason coal	0-6
Mason clay	3-0
Upper Mahoning shale and /or sandstone	30-0
Mahoning coal	0-10
Thornton clay	5-6
Mahoning limestone, nodular	4-6
Lower Mahoning sandstone and/or shale	35-0



Upper Freeport coal	1-6
Upper Freeport clay	5-0
Upper Freeport limestone	2-0
(Bolivar coal absent)	
Bolivar clay	5-6
Upper Freeport sandstone and/or shale	20-0
Lower Freeport coal	1-6
Lower Freeport clay	4-0
Unnamed shale	4-0
Lower Freeport limestone, nodular	6-0
Lower Freeport shale and/or sandstone	25-0
Washingtonville shale	(?)
Middle Kittanning coal	5-6
Middle Kittanning clay	4-0
Middle Kittanning shale*	(?)
Strasburg coal	0-4
Oak-Hill clay	7-0
Strasburg shale and/or sandstone*	10-0
Hamden limestone, nodular, marine	(?)
Unnamed shale	9-0
Lower Kittanning coal	2-0
Lower Kittanning clay	5-3
Kittanning shale and/or sandstone	6-0
Ferriferous ironstone	0-6
Vanport flint, marine	1-0
(Scrubgrass clay and coal absent)	
Scrubgrass sandstone*	9-0
Clarion coal	0-6
Clarion clay	3-0
Clarion shale	42-0
Putnam Hill limestone,, marine	1-6
Brookville coal	0-7
Brookville clay	4-0
Homewood sandstone and/or shale	15-0
Tionesta coal	0-6
Tionesta clay	6-6
Tionesta shale and/or sandstone*	5-0
Upper Mercer flint, marine	2-0
Bedford coal	0-9
Bedford clay	3-0
Bedford shale and/or sandstone*	17-0
Lower Mercer limestone, marine	2-0
Middle Mercer coal	1-0
Middle Mercer clay	3-6
Middle Mercer shale and/or sandstone*	4-0
Flint Ridge coal	1-0
Flint Ridge clay	4-0
Flint Ridge shale and/or sandstone	13-0
Boggs member, marine	1-0
Unamed shale	3-0
Lower Mercer coal	1-0
Lower Mercer clay	3-6
Lower Mercer shale and/or sandstone*	10-0
(Lovellville or Poverty Run limestone absent)	
Vandusen coal	1-0
Vandusen clay	3-6
Vandusen shale and/or sandstone*	10-0



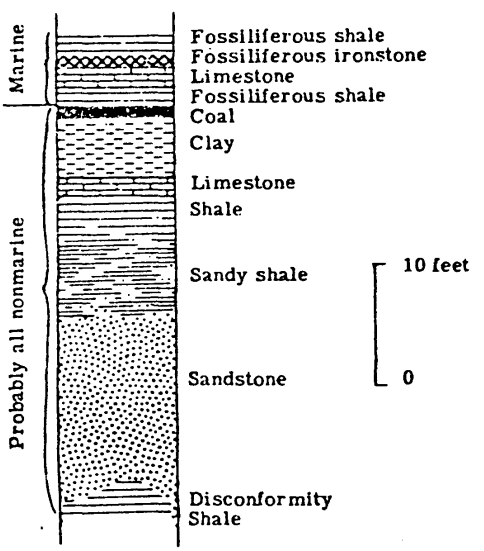


Diagram of a composite cyclothem of the Perry County, Ohio Column

LEGEND

ACID MINE DRAINAGE

Oxidation of Pyrite:

1) $FeS_{2(s)} + 3.5\ O_2 + H_2O \longrightarrow Fe^{+2} + 2\ SO_4^{-2} + 2H^+$

Ferrous Iron $\longrightarrow$ Ferric Iron:

2) $Fe^{+2} + 0.25\ O_2 + H^+ \longrightarrow Fe^{+3} + 0.5\ H_2O$

Precipitation of $Fe(OH)_3$:

3) $Fe^{+3} + 3H_2O \longrightarrow Fe(OH)_{3(s)} + 3H^+$

Over-All Reactions:

4) $FeS_{2(s)}$ (solid pyrite) $+ 3.75\ O_2$ (oxygen) $+ 3.5\ H_2O$ (water) $\longrightarrow$

$Fe(OH)_{3(s)}$ (Ferric Hydroxide-Red Precipate) $+ 2\ H_2SO_4$ (Sulfuric Acid)

5) $FeS_{2(s)} + 3.5\ O_2 + H_2O \longrightarrow FeSO_4 + H_2SO_4$ (soluble ferrous sulfates)

Figure 17. The basic chemical reactions in acid-mine drainage

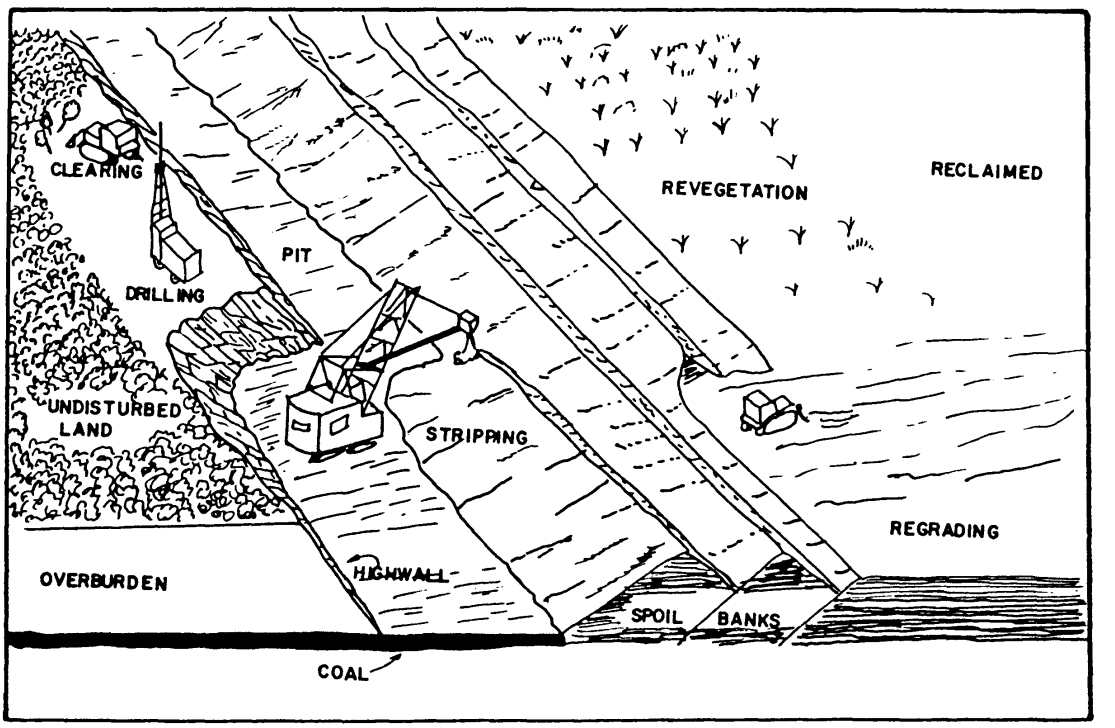


Figure 18. Area mining with concurrent reclamation (after Grim & Hill, 1974).

ANALYSIS OF WATER SAMPLES

Conversion factors for quality-of-water data

[U.S. gallon is used for all units involving gallons]

To convert—	To—	Multiply by—
Grains per gallon	Milligrams per liter	17. 12
Milligrams per liter	Grains per gallon	0. 05841
Milligrams per liter	Tons per acre-foot	. 001360
Milligrams per liter	Tons per day	second-feet × 0. 002697
Tons per acre	Metric tons per hectare	2. 2417
Parts per hundred thousand	Parts per million	10
Grams	Ounces (avoirdupois)	. 03527
Ounces (avoirdupois)	Grams	28. 35
Gallons (Imperial)	Gallons (U.S.)	1. 2009
Liters	Quarts (U.S.)	1. 057
Quarts (U.S.)	Liters	. 9463
Second-foot days[a]	Acre-feet	1. 983471
Second-feet[b]	Gallons per minute	448. 8
Second-foot days	Gallons per day	646, 317
Acre-feet[c]	Gallons	325, 851
Acre-feet	Cubic feet	43, 560
Cubic feet	Cubic meters	. 028317
Cubic feet	Gallons	7. 481
Ca^{+2}	$CaCO_3$	2. 497
$CaCl_2$	$CaCO_3$	. 9018
HCO_3^-	$CaCO_3$	. 8202
HCO_3^-[d]	CO_3^{-2}	. 4917
Mg^{+2}	$CaCO_3$	4. 116
Na_2CO_3	$CaCO_3$	. 9442
NO_3^-	N	. 2259
N	NO_3^-	4. 4266

[a] 1 sec-ft day = 1 cfs for 24 hr.
[b] 1 sec-ft = 1 cfs.
[c] 1 acre-ft = an area of 1 acre 1 ft deep.
[d] In reaction $2HCO_3 = CO_3^{-2} + H_2O + CO_2$.

Figure 19. Conversion factors (Hem, pg. 81).

a.) **ACCEPTABLE RAW WATER QUALITY LEVELS FOR DRINKING WATER SUPPLY**

PARAMETER	LEVEL			REFERENCE
ALKALINITY, As $CaCO_3$	GE	30	mg/L	NATIONAL HEALTH & WELFARE, CANADA, 1969
ALKALINITY, As $CaCO_3$	LE	500	mg/L	NATIONAL HEALTH & WELFARE, CANADA, 1969
AMMONIA, As N	LE	0.5	mg/L	NATIONAL HEALTH & WELFARE, CANADA, 1969
ARSENIC, As As	LE	0.01	mg/L	NATIONAL HEALTH & WELFARE, CANADA, 1969
BARIUM, As Ba	LT	1.0	mg/L	NATIONAL HEALTH & WELFARE, CANADA, 1969
BORON, As B	LT	5.0	mg/L	NATIONAL HEALTH & WELFARE, CANADA, 1969
CADMIUM, As Cd	LT	0.01	mg/L	NATIONAL HEALTH & WELFARE, CANADA, 1969
CALCIUM, As Ca	LE	200	mg/L	NATIONAL HEALTH & WELFARE, CANADA, 1969
CHLORIDE, As Cl^-	LE	250	mg/L	NATIONAL HEALTH & WELFARE, CANADA, 1969
CHROMIUM, As Cr(VI)	LT	0.05	mg/L	NATIONAL HEALTH & WELFARE, CANADA, 1969
COLOUR	LE	15	TCU	NATIONAL HEALTH & WELFARE, CANADA, 1969
COPPER, As Cu	LE	1.0	mg/L	NATIONAL HEALTH & WELFARE, CANADA, 1969
CYANIDE, As CN^-	LE	0.01	mg/L	NATIONAL HEALTH & WELFARE, CANADA, 1969
FLUORIDE, As F^-	LE	1.4	mg/L	NATIONAL HEALTH & WELFARE, CANADA, 1969
HARDNESS, TOTAL, As $CaCO_3$	LT	500.0	mg/L	NATIONAL HEALTH & WELFARE, CANADA, 1969
IRON, DISSOLVED, As Fe	LE	0.3	mg/L	NATIONAL HEALTH & WELFARE, CANADA, 1969
LEAD, As Pb	LT	0.05	mg/L	NATIONAL HEALTH & WELFARE, CANADA, 1969
MAGNESIUM, As Mg	LE	150	mg/L	NATIONAL HEALTH & WELFARE, CANADA, 1969
MANGANESE, As Mn	LE	0.05	mg/L	NATIONAL HEALTH & WELFARE, CANADA, 1969
NITRATE + NITRITE, As N	LT	10.0	mg/L	NATIONAL HEALTH & WELFARE, CANADA, 1969
pH	GE	6.5		NATIONAL HEALTH & WELFARE, CANADA, 1969
pH	LE	8.3		NATIONAL HEALTH & WELFARE, CANADA, 1969
PHENOLIC SUBSTANCES, As PHENOL	LE	0.002	mg/L	NATIONAL HEALTH & WELFARE, CANADA, 1969
PHOSPHORUS, TOT.INORG., As P	LE	0.2	mg/L	NATIONAL HEALTH & WELFARE, CANADA, 1969
SELENIUM, As Se	LT	0.01	mg/L	NATIONAL HEALTH & WELFARE, CANADA, 1969
SULPHATE, As SO_4^{2-}	LE	500	mg/L	NATIONAL HEALTH & WELFARE, CANADA, 1969
SULPHIDE, As H_2S	LE	0.3	mg/L	NATIONAL HEALTH & WELFARE, CANADA, 1969
TOTAL DISSOLVED SOLIDS	LE	1000	mg/L	NATIONAL HEALTH & WELFARE, CANADA, 1969
TURBIDITY	LE	5	JTU	NATIONAL HEALTH & WELFARE, CANADA, 1969
URANYL ION, As UO_2^{2-}	LE	5.0	mg/L	NATIONAL HEALTH & WELFARE, CANADA, 1969
ZINC, As Zn	LE	5.0	mg/L	NATIONAL HEALTH & WELFARE, CANADA, 1969

Figure 20a. (after McNeely and Neimanis).

b.) GUIDELINES FOR IRRIGATION OF ACIDIC SOILS

PARAMETER	LEVEL			REFERENCE
ALUMINUM, As Al	LE	5.0	mg/L	US. ENVIRONMENTAL PROTECTION AGENCY, R3.73.033
ARSENIC, As As	LE	0.10	mg/L	US. ENVIRONMENTAL PROTECTION AGENCY, R3.73.033
BERYLLIUM, As Be	LE	0.10	mg/L	US. ENVIRONMENTAL PROTECTION AGENCY, R3.73.033
BORON, As B	LE	0.75	mg/L	US. ENVIRONMENTAL PROTECTION AGENCY, R3.73.033
CADMIUM, As Cd	LE	0.010	mg/L	US. ENVIRONMENTAL PROTECTION AGENCY, R3.73.033
CHROMIUM, As Cr	LE	0.1	mg/L	US. ENVIRONMENTAL PROTECTION AGENCY, R3.73.033
COBALT, As Co	LE	0.050	mg/L	US. ENVIRONMENTAL PROTECTION AGENCY, R3.73.033
COPPER, As Cu	LE	0.20	mg/L	US. ENVIRONMENTAL PROTECTION AGENCY, R3.73.033
FLUORIDE, As F^-	LE	1.0	mg/L	US. ENVIRONMENTAL PROTECTION AGENCY, R3.73.033
IRON, As Fe	LE	5.0	mg/L	US. ENVIRONMENTAL PROTECTION AGENCY, R3.73.033
LEAD, As Pb	LE	5.0	mg/L	US. ENVIRONMENTAL PROTECTION AGENCY, R3.73.033
LITHIUM, As Li	LE	2.5	mg/L	US. ENVIRONMENTAL PROTECTION AGENCY, R3.73.033
MANGANESE, As Mn	LE	0.20	mg/L	US. ENVIRONMENTAL PROTECTION AGENCY, R3.73.033
MOLYBDENUM, As Mo	LE	0.010	mg/L	US. ENVIRONMENTAL PROTECTION AGENCY, R3.73.033
NICKEL, As Ni	LE	0.2	mg/L	US. ENVIRONMENTAL PROTECTION AGENCY, R3.73.033
pH	GE	4.5		US. ENVIRONMENTAL PROTECTION AGENCY, R3.73.033
pH	LE	9.0		US. ENVIRONMENTAL PROTECTION AGENCY, R3.73.033
SELENIUM, As Se	LE	0.02	mg/L	US. ENVIRONMENTAL PROTECTION AGENCY, R3.73.033
SODIUM ABSORPTION RATIO	LT	8		AUSTRAL. WATER RESOURCES COUNCIL, TECH. PAPER 7
VANADIUM, As V	LE	0.10	mg/L	US. ENVIRONMENTAL PROTECTION AGENCY, R3.73.033
ZINC, As Zn	LE	2.0	mg/L	US. ENVIRONMENTAL PROTECTION AGENCY, R3.73.033

c.) GUIDELINES FOR FOOD PROCESSING INDUSTRIES

PARAMETER	LEVEL			REFERENCE
ALKALINITY, As $CaCO_3$	LE	150	mg/L	ONTARIO, MINISTRY OF THE ENVIRONMENT, 1974
CHLORIDE, As Cl^-	LE	250	mg/L	ONTARIO, MINISTRY OF THE ENVIRONMENT, 1974
FLUORIDE, As F^-	LE	1	mg/L	ONTARIO, MINISTRY OF THE ENVIRONMENT, 1974
HARDNESS, As $CaCO_3$	LE	150	mg/L	ONTARIO, MINISTRY OF THE ENVIRONMENT, 1974
IRON, As Fe	LE	0.2	mg/L	ONTARIO, MINISTRY OF THE ENVIRONMENT, 1974
MANGANESE, As Mn	LE	0.2	mg/L	ONTARIO, MINISTRY OF THE ENVIRONMENT, 1974
NITRATE, As N	LE	10	mg/L	ONTARIO, MINISTRY OF THE ENVIRONMENT, 1974
NITRITE, As N		ND	mg/L	ONTARIO, MINISTRY OF THE ENVIRONMENT, 1974
ODOUR		ND	TON	ONTARIO, MINISTRY OF THE ENVIRONMENT, 1974
pH	GE	6.5		ONTARIO, MINISTRY OF THE ENVIRONMENT, 1974
pH	LE	8.5		ONTARIO, MINISTRY OF THE ENVIRONMENT, 1974
PHENOLIC MATERIAL, As PHENOL		ND	mg/L	ONTARIO, MINISTRY OF THE ENVIRONMENT, 1974
SILICA, As SiO_2	LE	50	mg/L	ONTARIO, MINISTRY OF THE ENVIRONMENT, 1974
SULPHATE, As SO_4^{2-}	LE	250	mg/L	ONTARIO, MINISTRY OF THE ENVIRONMENT, 1974
SUSPENDED SOLIDS	LE	10	mg/L	ONTARIO, MINISTRY OF THE ENVIRONMENT, 1974
TOTAL DISSOLVED SOLIDS	LE	500	mg/L	ONTARIO, MINISTRY OF THE ENVIRONMENT, 1974
TURBIDITY		ND	JTU	ONTARIO, MINISTRY OF THE ENVIRONMENT, 1974

d.) GUIDELINES FOR ELECTRICAL UTILITIES (HIGH PRESSURE STEAM GENERATION)

PARAMETER	LEVEL			REFERENCE
ALKALINITY, As $CaCO_3$	LE	1	mg/L	US. ENVIRONMENTAL PROTECTION AGENCY, R3.73.033
ALUMINUM, As Al	LE	0.01	mg/L	US. ENVIRONMENTAL PROTECTION AGENCY, R3.73.033
BICARBONATE, As HCO_3	LE	0.5	mg/L	US. ENVIRONMENTAL PROTECTION AGENCY, R3.73.033
CALCIUM, As Ca	LE	0.01	mg/L	US. ENVIRONMENTAL PROTECTION AGENCY, R3.73.033
COPPER, As Cu	LE	0.01	mg/L	US. ENVIRONMENTAL PROTECTION AGENCY, R3.73.033
HARDNESS, TOTAL, As $CaCO_3$	LE	0.07	mg/L	US. ENVIRONMENTAL PROTECTION AGENCY, R3.73.033
IRON, As Fe	LE	0.01	mg/L	US. ENVIRONMENTAL PROTECTION AGENCY, R3.73.033
MAGNESIUM, As Mg	LE	0.01	mg/L	US. ENVIRONMENTAL PROTECTION AGENCY, R3.73.033
MANGANESE, As Mn	LE	0.01	mg/L	US. ENVIRONMENTAL PROTECTION AGENCY, R3.73.033
OXYGEN, DISSOLVED, As O_2	LE	0.007	mg/L	US. ENVIRONMENTAL PROTECTION AGENCY, R3.73.033
pH	GE	8.8		US. ENVIRONMENTAL PROTECTION AGENCY, R3.73.033
pH	LE	9.4		US. ENVIRONMENTAL PROTECTION AGENCY, R3.73.033
SILICA, As SiO_2	LE	0.01	mg/L	US. ENVIRONMENTAL PROTECTION AGENCY, R3.73.033
SUSPENDED SOLIDS	LE	0.05	mg/L	US. ENVIRONMENTAL PROTECTION AGENCY, R3.73.033
TOTAL DISSOLVED SOLIDS	LE	0.5	mg/L	US. ENVIRONMENTAL PROTECTION AGENCY, R3.73.033
ZINC, As Zn	LE	0.01	mg/L	US. ENVIRONMENTAL PROTECTION AGENCY, R3.73.033

e.) GUIDELINES FOR THE PROTECTION OF FRESHWATER AQUATIC LIFE

PARAMETER	LEVEL			REFERENCE
ALDRIN	LE	0.001	µg/L	INTERNATIONAL JOINT COMMISSION, 1976
ALKALINITY, As $CaCO_3$	GT	20	mg/L	US. ENVIRONMENTAL PROTECTION AGENCY, 440/9-76023
BERYLLIUM, As Be	LE	0.011	mg/L	US. ENVIRONMENTAL PROTECTION AGENCY, 440/9-76023
γ-BHC (LINDANE)	LE	0.01	µg/L	US. ENVIRONMENTAL PROTECTION AGENCY, 440/9-76023
CADMIUM, As Cd	LE	0.003	mg/L	US. ENVIRONMENTAL PROTECTION AGENCY, 440/9-76023
CHLORDANE	LE	0.01	µg/L	US. ENVIRONMENTAL PROTECTION AGENCY, 440/9-76023
CHROMIUM, As Cr(VI)	LE	0.05	mg/L	GREAT LAKES WATER QUALITY BOARD, 1976
COPPER, As Cu	LE	0.005	mg/L	GREAT LAKES WATER QUALITY BOARD, 1976
CYANIDE, As CN^-	LE	0.005	mg/L	US. ENVIRONMENTAL PROTECTION AGENCY, 440/9-76023
p,p'- DDT	LE	0.003	µg/L	INTERNATIONAL JOINT COMMISSION, 1976
DIAZINON	LE	0.08	µg/L	GREAT LAKES WATER QUALITY BOARD, 1976
DIELDRIN	LE	0.001	µg/L	INTERNATIONAL JOINT COMMISSION, 1976
α-ENDOSULFAN	LE	0.003	µg/L	US. ENVIRONMENTAL PROTECTION AGENCY, 440/9-76023
β-ENDOSULFAN	LE	0.003	µg/L	US. ENVIRONMENTAL PROTECTION AGENCY, 440/9-76023
ENDRIN	LE	0.002	µg/L	INTERNATIONAL JOINT COMMISSION, 1976
GUTHION	LE	0.005	µg/L	GREAT LAKES WATER QUALITY BOARD, 1976
HEPTACHLOR	LE	0.001	µg/L	US. ENVIRONMENTAL PROTECTION AGENCY, 440/9-76023
IRON, As Fe	LE	0.3	mg/L	GREAT LAKES WATER QUALITY BOARD, 1976
LEAD, As Pb	LE	0.03	mg/L	US. ENVIRONMENTAL PROTECTION AGENCY, R3.73.033
MALATHION	LE	0.1	µg/L	US. ENVIRONMENTAL PROTECTION AGENCY, 440/9-76023
MERCURY, As Hg	LE	0.2	µg/L	GREAT LAKES WATER QUALITY BOARD, 1976
p,p'- METHOXYCHLOR	LE	0.03	µg/L	US. ENVIRONMENTAL PROTECTION AGENCY, 440/9-76023
MIREX	LE	0.001	µg/L	US. ENVIRONMENTAL PROTECTION AGENCY, 440/9-76023
NICKEL, As Ni	LE	0.025	mg/L	GREAT LAKES WATER QUALITY BOARD, 1976
OXYGEN, DISSOLVED, As O_2	GE	5.0	mg/L	US. ENVIRONMENTAL PROTECTION AGENCY, 440/9-76023
PARATHION	LE	0.008	µg/L	GREAT LAKES WATER QUALITY BOARD, 1976
pH	GE	6.5		US. ENVIRONMENTAL PROTECTION AGENCY, 440/9-76023
pH	LE	9.0		US. ENVIRONMENTAL PROTECTION AGENCY, 440/9-76023
PHENOLIC SUBSTANCES, As PHENOL	LE	0.001	mg/L	US. ENVIRONMENTAL PROTECTION AGENCY, 440/9-76023
POLYCHLORINATED BIPHENYLS	LE	0.001	µg/L	US. ENVIRONMENTAL PROTECTION AGENCY, 440/9-76023
SULPHIDE, As H_2S	LE	0.002	mg/L	US. ENVIRONMENTAL PROTECTION AGENCY, 440/9-76023
TOXAPHENE	LE	0.005	µg/L	US. ENVIRONMENTAL PROTECTION AGENCY, 440/9-76023
ZINC, As Zn	LE	0.03	mg/L	GREAT LAKES WATER QUALITY BOARD, 1976

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